Development of a Mechanical Means for Antipersonnel Landmine Neutralization

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by

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Abstract

Antipersonnel (AP) landmines are cheap and simple weapons used in warfare and other armed conflicts. The most effective and accepted form of landmine clearance is by manual demining, but this method is slow, laborious, costly and hazardous. The use of mechanical devices such as chain flails for landmine neutralization and/or area reduction has the potential of greatly aiding landmine clearance. However, mechanical clearance methods have not been fully accepted in the landmine clearance community due to a lack of knowledge and scientific data the actual soil-tool interaction and the landmine clearance effectiveness.

The research objective was to develop a mechanical device for the neutralization of AP landmines. The device was to deliver sufficient force to produce adequate ground deflection for detonation of typical AP landmines at depths up to 200 mm. Other design parameters included design simplicity, high durability with low and ease of maintenance and flexible operation.

A design matrix was employed to select an appropriate design for further analysis, resulting in preliminary testing and evaluation of off-the-shelf mechanisms, namely a Tamper and a Jackhammer. Key parameters included interaction pressure, sensor deflection and duty cycle. It was concluded that a tamper design resulted in superior demining capabilities. A final testing phase was designed and conducted to further research the effectiveness of the device and to determine optimal operational parameters between two shoe sizes and the number of pass applications. A test rig was designed and fabricated to attach the tamper system onto the Terra Mechanics Rig for test automation. Test results revealed that the small tamper shoe configuration performed better than a larger shoe, but only marginally so. Test results also indicated a two pass operation was optimal and that the proper shoe configuration is dependent on the demining environment. Furthermore, the large magnitudes of interaction pressure, deflection sensor displacement and total impulse indicate that the tamper system is capable of detonating AP landmines at depths of up to 200 mm.

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List of Nomenclature

A/D	Analog to digital
ANOVA	Analysis of variance
AP	Antipersonnel
APOPO	A Flemish acronym for Antipersonnel Mines Demining Product Development
AT	Antitank
ATSDR	Agency for Toxic Substances and Disease
CI	Cone Index
CROMAC	Croatian Mine Action Center
CCMAT	Canadian Centre for Mine Action Technologies
DRDC	Defense Research and Development Center
GICHD	Geneva International Center for Humanitarian Demining
LC	Load cell
MRM	Mechanically Reproduced Mine
R&D	Research and Development
TMR	Terra Mechanics Rig
TNT	b 2,4,6-Trinitrotoluene
UXO	Unexploded Ordinance
WORMs	Wirelessly Operated Reproduced Mine System

F	Force magnitude (N)
f_{impact}	Impact frequency (bps)
F_y	Vertical force component (N)
F_x	Horizontal force component (N)
KE	Kinetic energy (J)
H	Height (m)
i	Index increment
I_r	Moment of inertia (kg-m^2)
I	Impulse (N-s)

m	Mass (kg)
P	Vertical point load (N)
Pr	Pressure (Pa)
R	Polar position coordinate (m)
r	Position coordinate (m)
t	Time (s)
$T_{interaction}$	Interaction time (s)
v	Velocity (m/s)
v_h	Hammer tip velocity (m/s)
x	Displacement (mm)
V_o	Output Voltage (V)
Δt	Time increment (s)
θ	Impact angle (θ)
ξ	Concentration factor
σ_r	Normal vertical stress component (Pa)
β	Polar angle coordinate (rad)
ω	Angular velocity (rad/s)

CHAPTER I

INTRODUCTION

1.1 Background and Research Motivation

Antipersonnel (AP) landmines are inexpensive and simple weapons used in warfare and other armed conflicts. They are designed to re-route or construct a barricade to foot soldiers from a given area. AP landmines are not designed to kill, but to maim or severely injure persons. Landmines are indiscriminate in nature and have a prolonged existence, affecting both soldiers and civilians during times of peace and war. There are over 350 different types of landmines that contaminate over 70 countries. With more than 100 million landmines in the ground, 350 million in stock, and even more being laid at a rate of 2.5 million a year, landmines will be a significant problem for years to come (Shankhla, 2000).

A mechanical demining device can be defined as a ‘machine used to mechanically treat a mined area, cut vegetation and/or destroy landmines up to a depth of 200 mm (Steker, 2003). The primary reason for using mechanical demining is to enhance the demining process by increasing productivity and operator safety (Dirscherl, 2003; Griffiths and Kaminski, 2003). Due to variable and often incomplete clearance rates, mechanical demining is not used as a primary demining approach but is used in conjunction with other technologies and equipment, such as manual demining and dogs.

While there is great potential for the use of mechanical means of landmine neutralization, demining machines are in general, underused (Kaminski *et al.*, 2003). This can be related to the general skepticism and unacceptance by the demining community. Two important aspects relating to the lack of acceptance are identified as:

- A general lack of knowledge concerning the proper use of the devices, the effectiveness of landmine neutralization devices, and the dynamics associated with soil-tool interaction; and

- Operational and design problems that include improper use of technology, maintenance and durability problems, difficulties in mobility due to size and power requirements and cost effectiveness.

1.1.1 Insufficient Knowledge

The availability of knowledge concerning the proper usage and suitability of demining machines for differing environment and terrain conditions has not been thoroughly studied (Kaminski *et al.*, 2003; Handicap International Mines Co-ordination Unit, 2000; GICHD, 2004a). The demining effectiveness of most machines is not known. Demining organizations that operate machines in field conditions have not recorded the success rate or effectiveness of landmine neutralization, though some anecdotal evidence exists (Kaminski *et al.*, 2003). While there have been recent tests and evaluations on commercially available demining machines, the focus of these tests has been on operational characteristics such as slope climbing capabilities, traction, machine transportability and durability. It is uncommon for a machine to be tested for demining effectiveness in an objective and quantifiable method (Coley, 2002a). Also, there is limited scientific or experimental data concerning the technical reasons why landmines are missed or not destroyed (Kaminski *et al.*, 2003). A review of demining literature has exposed a general lack of research and data concerning the actual soil-tool interaction.

1.1.2 Operation and Design Problems

Many reports from demining organizations indicate that the use of “high tech”, complex and expensive mechanical demining equipment is not suitable for most demining applications, especially in developing countries (Tariq, 1998; Dirscherl, 2003; Habib, 2002; Handicap International, 2000). Many of the mine-afflicted countries are developing countries that cannot afford this type of equipment (Tariq, 1998). Due to the nature of mechanical demining, the equipment is subjected to extreme operating conditions such as weather, terrain and landmine blasts, resulting in high wear and tear, which subsequently limits the use of many high technology options (Tariq, 1998). Maintenance personnel and equipment operators in such countries have minimal formal education and the technological infrastructure needed to repair and service the equipment is poor to non-existent (Habib, 2002). In many situations, specialized equipment parts requiring machining or fabrication are not appropriate for on-field applications. Availability of off-the-shelf parts increases maintenance effectiveness and decreases costs (Dirscherl, 2003). When cost effectiveness is an issue, demining machines must operate continually with minimal servicing requirements. Some of the most successful and accepted demining machines have been adapted from commercial off-the-shelf parts or retro-fitted agriculture/forestry equipment (GPC International, 2002; Handicap International, 2000; GICHD, 2002; Hess, 1999). It has been noted that modular designs based on low cost-low technology have made large contributions to mechanical demining technology (Burke *et al.*, 2003; Handicap International, 2000).

Maintenance of many mechanical demining machines is of prime importance and tends to be based on design simplicity. Impact tools such as chain flails and tillers require high amounts of maintenance and part replacement (Habib, 2002). Many conventional flail systems have been removed from operation due to a lack of part availability and maintenance issues (Coley, 2002). An often stated factor contributing to the success of mechanical demining machines involves ease in repair of machines with a minimal amount of cost and time (Hess, 1999), as well as the ability to be repaired and maintained on site (Dirscherl, 2003).

A device used for mechanical demining must be able to operate in hostile conditions and withstand multiple blasts from AP landmines without suffering severe component damage (Habib, 2002). Commercial clearance machines go through a series of tests where the demining tool and demining vehicle are subjected to blasts from various amounts of explosive charges in order to evaluate the designs strengths (GICHD, 2004b). A contributing factor to the high maintenance costs is the general maintenance and replacement of parts, such as flails, hammers, teeth and chisels from general wear and tear (Habib, 2002; GICHD, 2004b).

Studies have shown that machines are severely limited by the terrain and weather conditions present in a given mine field (Tariq, 1998; GICHD, 2004b). Steker (2003) of the CROMAC Center for Testing, Development and Training, stated that the design goal is to ‘develop a machine that will be fully efficient in different conditions’.

The weight of the designs affects the power requirements for mobility. Heavier systems, such as tillers, require large, powerful engines need to power the tiller drum and the prime mover. Large, massive prime movers have many adverse effects, including environmental effects of soil compaction, mobility and transportation problems.

Problems of funding often limit many demining organizations to perform demining operations (Tariq, 1998; Habib, 2002). For machines to be of use, the cost of clearing one square meter of a mined area must be lower than traditional methods such as manual deminers and/or dogs (Dirscherl, 2003). Among many factors, the success of a machine depends heavily on the cost effectiveness of the design (Habib, 2002). The cost effectiveness of a machine is dependent on many factors, including but not limited to, power requirements, design performance, maintenance, durability, fabrication and/or acquisition costs and operator training.

1.2 Thesis Objectives

The main thesis objectives were: a) to develop a mechanical device for the neutralization of antipersonnel landmines; b) that the device was to deliver sufficient force to produce adequate ground deflection for detonating typical antipersonnel landmines at depths up to 200 mm. Design criteria included:

- design simplicity for minimizing production and repair costs;
- high durability with low cost and ease in maintenance;
- flexible operation with capabilities of neutralizing landmines over a variety of environmental conditions; and
- low power consumption or low cost of operation.

In developing a mechanical means for neutralizing landmines, the design process will include:

- developing a design/decision matrix for evaluating possible designs;

- advancing soil-machine interaction through experimental analysis, specifically, to investigate the effects tool geometry has on force and deflection transfer through soil; and
- conducting evaluation tests on the mechanism(s) in the University of Saskatchewan, Department of Agricultural and Bioresource Engineering soil bin facilities.

1.3 Thesis Overview

Introductory and background information pertaining to landmines and mechanical demining is presented in CHAPTER II *Literature Review*. CHAPTER III *Determination of the Optimal Solution* contains the design process used to select an optimal mechanical demining system. Possible designs were conceptualized. A set of evaluation parameters was selected and assessed. The design concepts were evaluated and ranked using a design matrix, resulting in the selection of two possible designs for further analysis. Preliminary testing and evaluation was performed on the top ranked designs. The details of the apparatus, methods and procedure, analysis, results and summary of the final testing phase appear in CHAPTER IV *Final Testing Phase*. CHAPTER V *Conclusions and Recommendations* summarizes the major contributions of the thesis project to mechanical demining. An evaluation summary of the final design along with recommendations for future research is also presented.

CHAPTER II

LITERATURE REVIEW

A summary of the research and development relating to the design and use of mechanical demining systems is contained herein. Background information on landmines and a review of demining methods and technology is followed by concepts relating to the soil-tool interaction of demining mechanisms and the subsequent interaction with buried landmines are also discussed.

2.1 Landmine Types

Landmines are defined by the International Mines Action Standards as ‘munitions designed to be placed under, on or near the ground or other surface areas, and are exploded by the presence, proximity or contact with a person or vehicle’ (UNMAS, 2001). Two common classifications for landmines are antipersonnel (AP mines) landmines and antitank landmine (AT mines.)

AP mines are specifically designed to be detonated in the presence, proximity or contact with humans (UNMAS, 2001). The AP mine function can be broadly classified as:

- protection for small military units and installations enabling a defensive position;
- protection of AT minefields from rapid hand breaching and investigation;
- covering blind avenues of approach from an enemy attack and provide early warning of infiltration; and
- deterring the removal of other obstacles as well as slowing the enemy (Roy, 2000).

Two basic types of AP mines include the blast mine and the fragmentation mine. Blast mines are typically small and cylindrical, with a diameter ranging from 60 – 140 mm and are usually encased in a plastic body. A typical blast mine, the PMN 2 is shown in Figure 2.1. The amount of Trinitrotoluene (TNT) in AP blast mines can range from 10 to 200 g of TNT and require a direct static force 19 to 250 N[1] (Canadian Forces, 2004), usually on the top surface of the mine, to initiate detonation. The small amount of explosive and the plastic body result in minimal fatalities, but can result in serious injury and maiming. Many AP blast mines contain minimum amounts of metal parts, making it difficult to locate using conventional methods, such as metal detectors.

Figure 2.1 A PMN 2 blast mine[2].

Fragmentation mines are munitions that break apart upon detonation, driving metallic fragments into the air, acting as ballistics. Fragmentation mines are often fatal due to the flying debris and can injure a number of people at once. These mines can be bounding or directional. A bounding mine refers to a type of AP mine that when activated, is

[1] Refer to Appendix A for details concerning unit allocation associated with landmine actuation and neutralization.

[2] Photograph reproduced from Trevelyn, J. (2000), Demining at the University of Western Australia, www.mech.uwa.edu.au/jpt/demining/info/pmn-2.html.

propelled approximately 1 meter into the air, at which point, the main charge is detonated. A directional landmine refers to a mine that when detonated, sends fragments in a planned intended direction. Both types are typically detonated by a tripwire or by remote command.

The operation of AP landmines differs from model to model, but the basic operation includes the use of a pressure sensing pad or trip wire, a firing mechanism and an amount of explosive. A typical blast mine, for example the “M14”, is composed of a load sensing pad, a Bellville spring, a firing pin, a detonator and main charge of 31 grams explosive. When a certain load is applied to the top of the load sensing pad (as low as 50 to 89 N) the Belleville spring collapses, pushing the firing pin onto the detonator, which ignites the main charge of TNT, detonating the landmine (Bonsor, 2003).

Antitank landmines (AT mines) are much larger and contain larger amounts of explosives compared to a blast mine. They are specifically designed for vehicles such as tanks. The minimum detonation force is much higher and is typically detonated by heavy objects such as vehicles.

2.2 Landmine Clearance and Demining Technologies

The Geneva International Center for Humanitarian Demining (GIHCD, 2005) defines mine action as “activities which aim to reduce the social, economic and environmental impacts of landmines and unexploded ordinances”. There are five foundations of mine action (E-mine, 2005):

- the removal and destruction of landmines and explosive remnants of war and the marking/fencing off of areas contaminated with them;
- mine-risk education of civilians to aid in understanding the risks, identifying mines and unexploded ordinance (UXO) and protecting themselves;
- medical assistance and rehabilitation services for landmines victims;
- the advocacy for a landmine free world and the encouragement of countries to participate in international treaties and convention; and
- aiding countries to destroy mine stockpiles.

Humanitarian demining is one of the core elements of mine action and includes demining activities, as well as surveying, mapping and minefield marking. The objective is to return safe land to the civilian population, in contrast with military demining, which focuses on clearing a path in a mined area quickly, without neutralizing all the potential threats.

The basic principle of mine clearance is the identification and removal of mine and UXO threats from a given area to a specified depth (usually 200 mm) with a goal of 100% landmine neutralization (GICHD, 2004a). A “tool kit” approach is often used for humanitarian clearance operations and is composed of manual and mechanical demining systems.

2.2.1 Manual Demining

Manual demining is considered to be the backbone of humanitarian demining and is considered by many to be the only way for guaranteed method of 100% landmine neutralization (GICHD, 2005). Manual demining utilizes metal detectors, manual soil prodding and detection animals, such as dogs, to locate and neutralize landmines. Manual demining is also used in conjunction with mechanical demining methods to increase productivity and safety, as well as providing quality assurance. Manual demining is a slow, expensive and hazardous task. Commercially stated productivity rates are around 50 m^2 per deminer per day, though independent studies claim this number is overstated and estimate a lower clearance rate of 15 to 20 m^2 per deminer per day (GIHCD, 2005). Clearance cost range from US $ 0.60 to $ 8.73 per square meter, depending on the terrain and other operational costs (GIHCD, 2005).

The use of animals such as rats and dogs to aid manual deminers in landmine detection has grown considerably in the demining industry. There are currently over 750 dogs being employed, mostly in Afghanistan and Iraq (GICHD, 2003a). Dogs are used as a detection tool as they can detect low concentrations of vapors emitted by landmines, and are able to discriminate between different vapors concurrently (GICHD, 2004a). Rats have emerged as a possible alternative to dogs, as they exhibit the same capability to detect low concentrations of landmine emissions, as well as offering other advantages such as being easier and faster to train, smaller and resilient in many environments (GICHD, 2003a). Only one organization, the Antipersonnel landmine demining product development organization (APOPO) is using and training rats as detection tools, and is employing them in areas of Mozambique (APOPO, 2005).

There has been much research dedicated to the constructing of landmine detection methods such as ground penetrating radar, infrared sensors and artificial vapor detection systems. These methods have had limited field success (GICHD, 2003a).

2.2.2 Mechanical Demining

The use of mechanical systems for demining operations was first employed by military organizations during World War One (Dirscherl, 2003). The primary use of such systems was to provide a breaching system in which a tank or other vehicle cleared a path in a minefield, providing a passageway for troops through a mined area, but not to demine the area. Devices such as rollers and chain flails were primarily employed. During the 1980's, demining activities shifted focus to humanitarian purposes. Humanitarian mechanical demining devices were adapted for the military machines such as rollers and chain flails.

The use of mechanical demining devices can be divided into three major areas (Griffiths and Kaminski, 2003; Green, 1999):

- primary ground processing - machines are used as the primary method of landmine clearance. Due to limited success rates, mechanical demining machines are not used as a primary clearance method at this time. Some researchers believe that with proper application, this may change soon as technology advances and application techniques improve (GIHDC, 2004b);
- area reduction - machines are used to locate perimeters of actual mined areas and aid in the identification and verification of a patterned minefield's borders. Research from organizations, such as, GIHDC, have determined that a major

portion of a clearance operation is spent on land devoid of landmines and have identified area reduction using mechanical demining devices as an area where the greatest increase in efficiency can be made (GICHD, 2004b; Griffiths and Kaminski, 2003; Handicap International Mines Co-ordination Unit, 2000); and

- ground preparation - most mechanical demining devices are used in conjunction with manual demining operations for ground preparation (GICHD, 2004; Dirscherl, 2003). Ground preparation techniques aid and increase the speed of manual demining. Vegetation, tripwires and metallic contamination is removed. Hard packed soil surfaces are broken up, metallic pieces are removed from the soil and the soil surface is then broken.

2.2.2.1 Mechanical Demining Operation Characteristics

Research has been focused on mechanical mine neutralization equipment which includes the following categories: chain flails, tillers, rollers and multi-tool or combined tools.

2.2.2.1.1 Chain Flail Systems

Currently, chain flails are the most common landmine neutralization method employed, with over 150 machines in use. Chain flail devices operate on the concept that a large impact force applied at the ground will detonate or fragment landmines on or near the soil surface. A typical chain flail system, the Aardvark Mk IV (Aardvark Clear Mine Ltd., Insch, Scotland) is shown below in Figure 2.2

Figure 2.2 The Aardvark Mk IV chain flail system[3].

[3]Photograph with permission from Aardvark Clear Mine Ltd., http://www.landmineclearance.com/page11.html.

Chains are attached to a central rotating drum with weights of varying geometry pinned to the end. As the central shaft rotates at high speeds, the end masses strike the ground, delivering a large impact force to the soil which is capable of detonating or fragmentizing landmines. The force delivered to the soil is dependent on the rotational speed, flail translational velocity, chain length, end mass and geometry. Chain flails have also been utilized for ground preparation, due to the vegetation and trip wire clearing capabilities of the chains themselves.

There are many models of chain flail machines which are grouped according to the total weight of the unit; the three categories are light, medium and heavy. A large variation in system and operational parameters exists, with many new, independently untested machines available in each category. Typical functional parameters for the chain flails systems, as evaluated by the GICHD (2004c), are tabulated below in 0. The effectiveness of the chain flail has been proven, but the chain flail suffers deficiencies such as throwing mines in cleared areas (possibly live), large dust clouds which can affect the prime mover performance and a lack of acceptance in the landmine community (Shankhla, 2000; Hess, 1999).

Table 2.1 Chain flail system parameters (GICHD, 2004c).

Parameters	Mini		Medium		Heavy	
	Average	Range	Average	Range	Average	Range
Mine clearing capability	Both AP and AT		Both AP and AT		Both AP and AT	
Clearing/neutralizing mechanism specification	55 chains	31 – 108 chains	68 chains	48 – 72 chains	1 to 2 flail systems	
Clearance width (mm)	1600	1100 - 2100	2700	2000 - 3500	3400	2700 - 4000
Clearance depth (mm)	186	150 – 350	280	200 -500	250	200 - 300
Clearance rate (m^2/h)	500	Newer machines : 3700 but untested	1250	(high variability)	2700	140 – 8000
Mode of motion	Both track and wheel		Tracks most common		Track and wheel	
Mass of machine (kg)	5400	2500 - 7000	12,000	7,800 – 18,000	35,000	32,000 – 35,500
Mass of flail unit (kg)	Unknown		2.,500	1,500 – 4,300	11,300	8,300 – 19,900
Fuel requirement (L/h)	12.5	7 – 35	22	9 – 60	47	17 – 80
Cost (US)	$250,000 US	$110,000 – $450,000	$325,000 US		$1,000,000 (limited data)	
Number in use	70		73		10 (Scanjack very popular)	
Maneuverability	Very maneuverable		Fairly good, limited with increased size		Limited – heavy and bulky	
Transportability	By trailer/air or self propelled		By trailer or self propelled		Need lowbed trailer for transport	
Control	Remote		Operator controlled and remote		Operator controlled	

AP = Antipersonnel landmine
AT = Antitank landmine

2.2.2.1.2 Tiller and Roller System

Tiller systems were initially used for forestry equipment and designed to grind large tree stumps and/or rocks (Kaminski and Griffiths, 2003) and have since evolved into landmine clearance devices. A Mine-Guzzeler Tiller system (BAE Systems Bofors, Karlskoga, Sweden) is shown in Figure 2.3. Tiller machines operate on a similar premise to the flail systems, where a rotating drum fitted with hardened chisels or teeth is ploughed along the surface of the soil. The rotating teeth strike landmines causing detonation or fragmentation. Tiller machine usage has been limited, with approximately ten commercial models in use (GICHD, 2004c). Tiller systems tend to be expensive, large and heavy machines which are difficult to maneuver and transport. Typical functional parameters for the tiller systems, based on five commercial systems, are presented in Table 2.2.

Figure 2.3 A Mine-Guzzler Tiller system[4].

Rollers are also used to detonate landmines by applying a surface load. Rollers are often placed in front of a vehicle's wheels or tracks and are used for area reduction applications. The effectiveness of rollers systems for humanitarian demining applications is limited (Heiss, 1999).

[4] Photograph reproduced from GICHD (2004). Mechanical demining equipment catalogue 2004, Geneva, Switzerland: Geneva International Center for Humanitarian Demining, page 80.

Table 2.2 Tiller system parameters (GICHD, 2004c).

Parameters	Tiller	
	Average	Range
Mine clearing capability	Both AP and AT	
Clearing/neutralizing mechanism specification	1 to 3 rotating drums 280 teeth	66 – 500 teeth
Clearance width (mm)	3200	2500 - 3700
Clearance depth (mm)	440	200 – 500
Clearance rate (m^2/h)	1500	225 – 4000
Mode of motion	Track	
Mass of machine (kg)	48,000	38,000 – 58,000
Mass of tiller unit	11,000	6,000 – 15,000
Fuel requirement (L/h)	110	60 – 200
Cost	1,500,000 (based on one commercial machine)	
Number in use	10	
Maneuverability	Difficult due to size and weight	
Transportability	By trailer or self propelled (slow road speed)	
Control	Remote and operator controlled	

AP = Antipersonnel landmine
AT = Antitank landmine

2.2.2.1.3 Combination or Toolkit Systems

Combined landmine clearance systems are machines that specifically integrate two or more demining methods to further eliminate and increase neutralization efficiency. Only two commercial machines appear to exist and these are still in the development stage. An example includes the Redbus Land Mine Disposal System (GICHD, 2004c) shown in Figure 2.4, which utilizes two machines. One using hydraulic cylinders fitted with impacting feet that strike the ground repeatedly to detonate landmines. The second breaks up the ground, removes metallic remnants and further crushes any remaining explosives.

Some manufacturers have used a multi-tool approach, in which a prime mover is used in conjunction with a variety of demining tools. The tools can be interchanged, depending on the terrain at hand. Tool types, range from ground preparation tools (brush cutters, sifter, backhoes) to smaller demining flail and tiller systems. Many of these machines are still in the developmental stages with limited testing and evaluation having been conducted.

Figure 2.4 The Redbus Land Mine Disposal System[5].

2.3 Research and Theoretical Aspects Relating To Mechanical Landmine Neutralization

There has been very little research conducted that relates the soil-tool interaction of mechanical demining tools, though a small body of experimental and theoretical knowledge has been collected regarding the dynamic soil-tool interaction, such as, the impact strike and energy transfer to soil of chain flails. The chain flail strike interaction is similar to other dynamic impacting devices, such as the Mine Hammer, tamper systems and to a lesser extent roller system (Stilling, 2003). Thus, the chain flail interaction can be used to characterize common key concepts and parameters needed to understand the soil-tool interaction of such devices. Key concepts include:

- kinetic energy of the system;
- force transfer of the tool;
- soil-tool interaction;

[5]Photograph reproduced from GICHD. 2004. Mechanical demining equipment catalogue 2004, Geneva, Switzerland: Geneva International Center for Humanitarian Demining, page 102.

- stress distribution of an impact, and
- the dynamic interaction of an incoming pressure wave and a buried landmine.

The following sections introduce some of the basic concepts used by researchers in analyzing these keys concepts.

2.3.1 Energy Transfer

Chain flail devices are composed of a series of chains spaced across a rotating rotor. At the end of the chain, a mass, called a hammer is attached. As the rotor spins, the hammer is moved through the air, developing a kinetic energy related to the rotational velocity, the chain length and the mass of the hammer. By neglecting the mass of the chain and the forward travel speed of the system, the general equation for the total energy of the system the moment before hammer impact is shown in equation 2.1[6]. It is important to note that the actual force imparted to the soil is complex and is dependant on operational and soil characteristics. Operational characteristics may include forward travel speed, impact angle, chain length and mass, number of chain segments, the dynamic interaction between chain links, depth of hammer penetration and rebound effects during impact. Soil characteristics may include soil type, moisture content and stress history. Rubinstein *et al.* (1999) provided an example of a chain flail impact analysis.

$$KE = \frac{1}{2} m v_h^{\ 2} + \frac{1}{2} I_r \omega^2 \tag{2.1}$$

where

KE = kinetic energy (J),

m = mass of impacting tool (kg),

v_h = tip velocity of the hammer at the moment of impact (m/s) due to its rotation,

I_r = moment of inertia of the end mass (hammer) (kg•m^2)

and ω = angular velocity of the end mass (hammer) at the moment of impact (rad/s).

It is important to note that the kinetic energy is a scalar quantity and has no bearing on the direction of travel of the flail. The actual amount of energy that would be available

[6] Refer to Appendix A for details concerning unit allocation concerning impact energy and force.

for impacting the ground will depend on operational characteristics, soil parameters and terrain.

2.3.2 Impact Force

During impact, a transfer of kinetic energy of the impacting tool to the soil results in the force being applied to the soil surface. As discussed in the Section *2.3.1* Energy Transfer, the magnitude of this force is heavily dependant on the operational characteristics of the impacting tool and soil characteristics. A schematic of a typical chain flail configuration, as shown in Figure 2.5, is composed of a chain of length *l*, rotating about a point at a distance, *H* above the ground surface, and a hammer impacting the ground (position A).

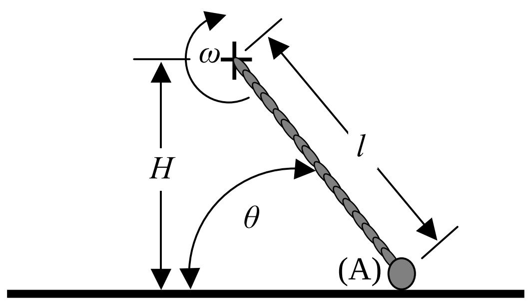

Figure 2.5 A typical chain flail configuration.

Shankhla (2000) presented a model containing key parameters influencing the contact forces between chain flail based devices and soil. An equation for an average impact force was expressed as a function of hammer mass (*m*), angular velocity (ω), flail radius (*l*) and stopping time (*t*), as given by the equation:

$$F = \frac{m\omega l}{t} \tag{2.2}$$

It was noted that the stopping time in equation 2.2 is a function of the chain flail operational parameters as well as soil characteristics. Assuming that the impact angle is constant (θ), the impact force can be further expressed as a vertical (F_y) and a horizontal force component (F_x), defined by the equations:

$$F_x = F\sin\theta \tag{2.3}$$

$$F_y = F\cos\theta \tag{2.4}$$

where θ is the impact angle shown in Figure 2.5.

Shankhla (2000) notes that the horizontal force component should be minimized as it aids in the creation of soil displacement, overburden, ridges and mine scattering, while the vertical force should be maximized, as the force penetrates deeper into the soil.

Shankhla (2000) also analyzed the effects of various chain flail configurations and end mass geometry. It was noted that the use of sharp-edged end mass geometries should be avoided due to increased soil penetration and movement, resulting in an increased risk of displacing a mine without neutralizing it. A spherical or round shape was recommended. Also noted was the role of the multiple degrees of freedom with respect to chain flails, which introduced instability in the flail systems when impacts occur. This instability causes the chain flails to meander, leaving skip zones.

The significance of the parameters of the above equations, namely impact angle, hammer mass, chain radius and stopping time were studied by researchers at the Department of Agricultural and Bioresource Engineering, University of Saskatchewan. The effects of soil compaction, impact angle and rotational speed on the magnitude and temporal pattern of force transferred to depth were investigated (Kushwaha *et al.*, 2004; Sharifat and Kushwaha, 2001) with the following conclusions referring to operational characteristics being made:

- increasing the hammer mass increased the force and impulse load transferred through the soil;
- increasing the rotational speed of the chain flails resulted in an increased load transferred through the soil;
- increasing the impact angle increased the force and impulse load transferred through the soil, primarily due to the increased vertical force component;
- increasing the levels of soil compaction resulted in increased force and impulse transfer;
- increasing the depth of the force sensor resulted in decreases to the force and impulse load transferred; the soil attenuated force transfer as larger force and

impulse magnitudes were observed when the load cells was buried closer to the point of impact;

- increasing the sensor interface area resulted in larger measured force and impulse; the interface area (or pressure sensing area) of the load cells heavily influenced the magnitude of the measured force and impulse; and
- maximum forces and impulses were observed to occur directly above the buried sensors.

Further studies were conducted on the effects of various chain flail hammer geometries, including an open chain, a spherical hammer, a cubic end mass, a chisel end mass and a prototype design called the mine hammer (Stilling *et al.*, 2003). Conclusions based on hammer geometry were as follows:

- The spherical hammer produced the most consistent impact pattern, while the cubical hammer and chisel produced erratic temporal force patterns characterized by high and low force peaks. It was hypothesized that the peaks were due to the sharp edges of the hammers striking the ground, while the low peaks were due to impact strikes deviating from a linear strike path.
- It was observed that the strike pattern for all the chain flails deviated from the straight line path of travel. The degree of deviation was observed to be dependent on soil compaction and tool geometry. Higher soil compaction resulted in large deviations. The spherical hammer deviated the least from the path, followed by the chisel, cube and open chain.

2.3.3 Soil Stress Distribution Due to Loading

A common method of estimating the pressure distribution in soils due to static loading is based on the Boussinesq equation (Smith *et al.*, 2000*)*. The Boussinesq equation predicts the stress distribution of a soil by assuming that the soil is elastic, homogeneous, isotropic, weightless and a semi-infinite medium.

A elastic, isotropic cube of soil is located at a position defined by the radial vector *R*, which is perpendicular to one side of the cube, as seen in Figure 2.6.

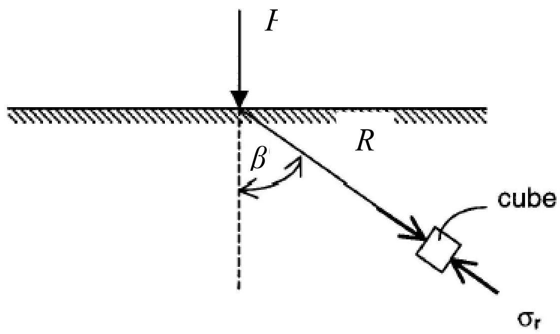

Figure 2.6 Soil stress due to vertical point load [7].

The normal vertical stress component on the soil cube as predicted by the Boussinesq equations (Sharifat and Kushwaha, 2000) is given by:

$$\sigma_r = \frac{3P}{2\pi R^2}\cos^3\beta \tag{2.5}$$

where

P = vertical point load,

R = polar position coordinate,

and β = polar angle coordinate.

To account for the non-elastic behavior of soil, a concentration factor, ζ, was introduced into the equation (Frolich, 1934, from Trautner 2003). The concentration factor is related to soil type, moisture content, stress history, soil contact area of the applied load and contact stress. Thus, equation (2.9) becomes:

$$\sigma_z = \frac{\zeta P}{2\pi R^2}\cos^{\zeta-2}\beta \tag{2.6}$$

It was later proposed that stresses will concentrate around the load axis and propagate deeper into soils of higher plasticity. Additional concentration factor values were later

[7] Figure reproduced form Sharifat, K. and R. L. Kushwaha. 2000. Modeling soil movement by tillage tools. *Canadian Agricultural Engineering* 42(4):166

presented accounting for differing soil plasticity (Sohne, 1953;, from Trautner 2003). The stress distribution can be considered to be circular in shape, though in reality, the actual stress distribution may not follow an exact circular pattern (Sharifat and Kushwaha, 2000). Concentration factor values for different soils and schematic representations of stress distributions under a point loading are presented in Figure 2.7. Suggested values for the concentration factor are 3 for a perfectly elastic isotropic mass, 4 for a hard soil, 5 for an average relatively dry soil and 6 for soft/wet soil (Trautner, 2003).

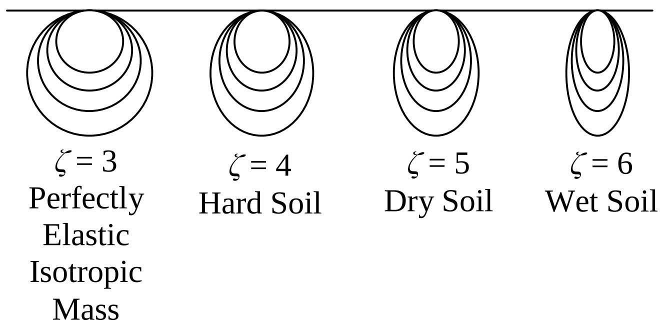

Figure 2.7 Concentration factors and schematic representation[8].

These factors have been studied to some extent in related fields such as the compaction and stress distribution from vehicular and agricultural traffic (Smith *et al.* 2000*)*. Studies have shown that when properly applied, the Boussinesq equation serves as a reasonable guide to predicting stresses in soils.

There has been little research concerning the pressure distribution in soils due to impact loading (Sharifat *et al.*, 2001). Sharifat and Kushwaha (2000) modeled soil movement due to high speed tillage tools by considering circular influence zones. It was assumed that the movement of soil particles is proportional to and in the direction of, the normal stresses as determined by the Boussinesq equation. The Boussinesq equation was also used to approximate soil stresses and ground-surface-level impact forces (Sharifat and Kushwaha, 2000). The results showed the Boussinesq solution underestimated the stresses in soil. Rubinstein and Wolf (1999) presented a basic model for ground surface

[8] Figure adapted form Sharifat, K. and R. L. Kushwaha. 2000. Modeling soil movement by tillage tools. *Canadian Agricultural Engineering* 42(4):166.

impact forces of a chain flail/soil impact using Hertz contact theory and modeling the soil as a linear elastic medium.

Shankhla (2000) extended the work done by Sharifat and Kushwaha (2000) on soil movement during high speed tillage to the interaction of a chain flail hammer strike with soil. Upon hammer impact, soil underneath the hammer fails and moves. The movement of soil particles depends on soil conditions. Soil directly underneath the hammer will move with the same velocity as the hammer. Due to the cohesive and adhesive properties of the soil, soil adjacent to the hammer is also displaced. Adjacent soil may move in a perpendicular direction to the hammer travel path, or may move with the hammer. The pattern of soil movement suggested that an influence zone existed. As a simplification, it was assumed that the influence zone has a circular shape which travels with the hammer as it penetrates the soil. It was also assumed that the movement of the soil particles was proportional to and in the direction of normal stresses, as predicted by the Boussinesq equation. The influence zone is composed of iso-intensity circles attached to each other at the hammer/soil contact point.

The magnitude and direction of soil movement depends on the location within the zone of influence and is proportional to the intensity of a corresponding circle. Smaller circles correspond to higher intensity and largest soil movement, while larger circles correspond to lower intensity and smaller soil displacement. Soil movement is perpendicular to a corresponding iso-intensity circle. Soil located outside the influence zone will not move. A schematic representation of the zone of influence and soil movement is shown in Figure 2.8. Arrows represent the soil velocity and the disks represent iso-intensity circles.

As the hammer penetrates and moves through the soil, the influence zone travels with it. Soil within the zone is displaced to a new position and again affected by another circle and attains a new position. The pattern of soil movement continues until the soil is outside the zone of influence. A landmine within the zone of influence will be subjected to a wave of pressure. The interaction between the landmine and pressure wave is a complicated process depending on several factors including relative position within the zone of influence, physical soil properties, landmine geometry, material properties and the mechanical structure.

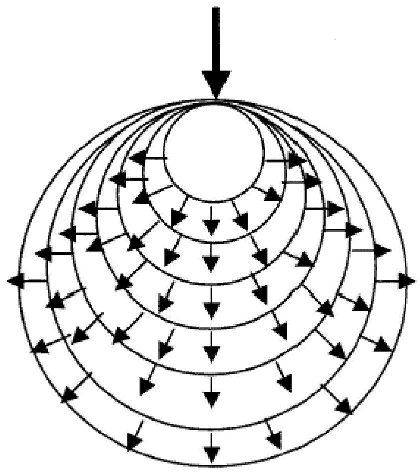

Figure 2.8 Schematic representation of the zone of influence and soil movement[9].

If a force is applied as a distributed load rather than a point source application, other factors must be taken into consideration. Distributed loading occurs when a load is applied over an area such as a plate. Flat plate loading or plate sinkage tests have been used in civil and terrain-vehicle engineering whereby lateral and axial stresses, soil deflection and compaction have been experimentally and theoretically studied. Of greatest importance to the study of landmine neutralization is the deformation associated from distributed loading. Earl and Alexandrou (2001) examined the soil deformation due to plate loading experimentally and verified "the theories of Prandlt, Terzaghi and Meyerhof". The three phases that soil undergoes during compression for a slowly applied load (10mm/s) on a small plate (150mm diameter) are shown in Figure 2.9. During phases 1 and 2, soil compaction occurs directly below the plate, while lateral deformation and axial compaction occur in phase 3. As shown in Figure 2.9, as penetration continues, a cone of compacted soil develops below the base of the plate, while the soil shears and moves laterally and upwards as illustrated in Figure 2.10. Studies related to a distributed, impact load were not available to contribute to the understanding of soil stress and strain or force transfer and resulting soil compaction and deformation at during this time.

[9] Figure adapted form Sharifat, K. and R. L. Kushwaha. 2000. Modeling soil movement by tillage tools. *Canadian Agricultural Engineering* 42(4):167.

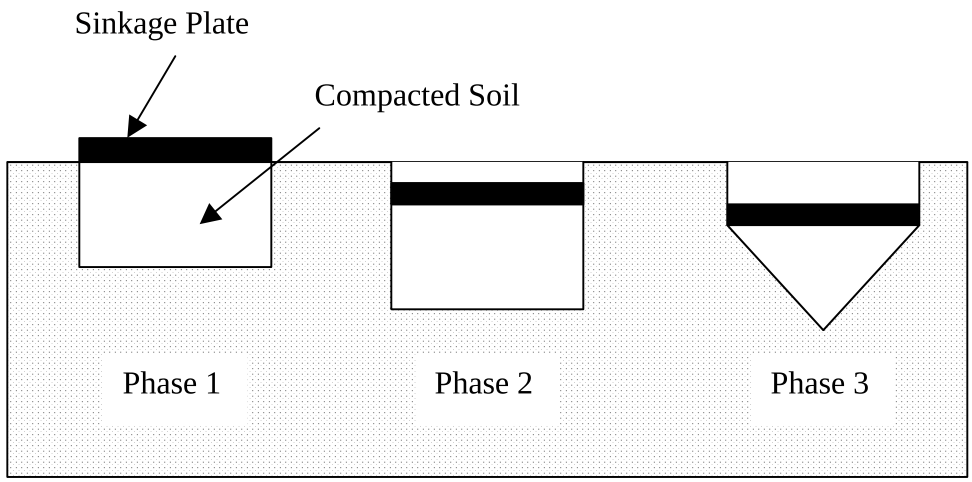

Figure 2.9 Deformation phases associated plate sinkage[10].

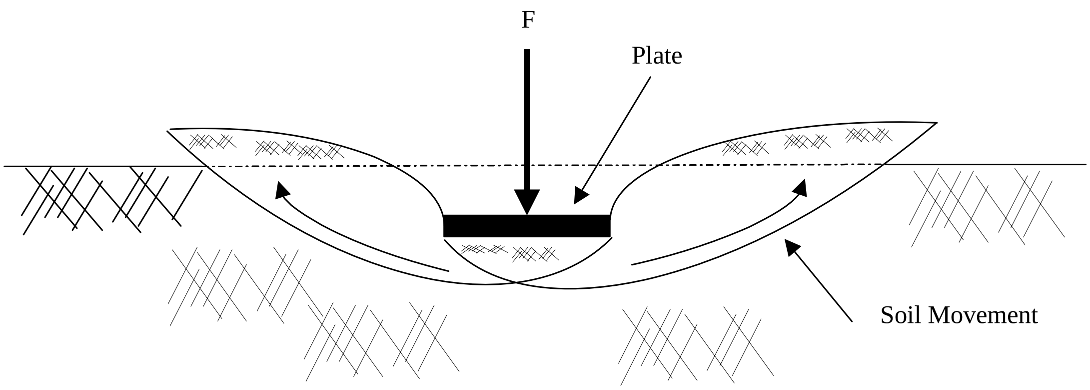

Figure 2.10 Shear planes due to plate loading.[11]

2.3.4 Dynamic Interaction between Pressure and Landmine

Research relating to the response of buried structures to dynamic surface loading is limited and usually related to civil engineering applications and wave propagation effects. A review of relevant literature exposed related interaction phenomena applicable to landmine neutralization due to repeated impact loads.

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[10] Figure adapted form Earl, R. and A. Alexandrou. 2001. Deformation processes below a plate sinkage test on sandy loam soil: experimental approach. *Journal of Terramechanics* 38:154.
[11] Figure adapted from McKyes, E. 1989. Agricultural Engineering Soil Mechanics. New York, NY: Elsevier Science Publishing Company Inc.

Researchers have studied the response of buried structures to impact loading using experimental and analytical techniques relating to wave propagation. It has been verified experimentally and numerically that the dynamic loading of buried structures can result in load relief on the structure (Chen *et al.*, 1990; Chen and Chen, 1996; Dancygier and Karinski, 1999). Two influential aspects of load relief are static soil arching and dynamic soil arching. Static soil arching refers to a mechanism relating to the shear strength and relative displacements in soil above flexible portions of a buried structure such as a buried room (Dancygier and Karinski, 1999a) or, as an extension, a buried landmine. The center of the span deflects due to an applied pressure, altering the interaction pressure field. The result is a decrease in sensed load at the center and an increase at the sides or supports.

As described by Chen and Chen (1996), dynamic soil arching relates to the dynamic soil-structure interaction due to a dynamic load propagating through a soil. When a pressure wave propagates through a soil and interacts with the top surface of a buried structure, two phases of interaction occur, as shown in Figure 2.11.

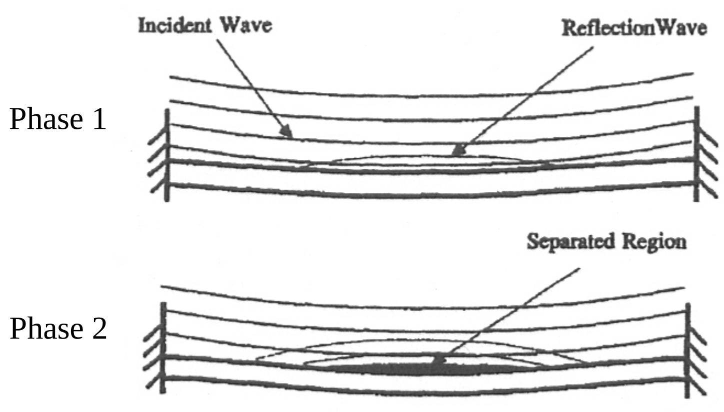

Figure 2.11 Schematic of dynamic arching[12].

In phase 1, the load is gradually applied to the surface. The resulting interaction pressure between the surface and the soil progressively increases to above zero. There is no

[12] Figure reproduced from Chen, H., and S. Chen. 1996. Dynamic response of shallow buried flexible plates subjected to impact loading. *Journal of Structural Engineering* 122(1):57.

separation between the interface surface and the soil. The interaction pressure is due to different traveling speeds between the soil, the structure and the incident pressure wave. In phase 2, the soil and the structure deflect at different velocities and eventually separate from each other. As a result, the interaction pressure in the region of separation becomes zero. Chen and Chen (1996) note that the process responsible for the soil separation is complicated and is related to the loading function, the buried plate stiffness and the characteristics of the soil.

Chen and Chen (1996) determined that the stiffness of the interaction surface heavily influences the amount of load relief due to dynamic arching. Stiffer plates experience less deflection and less separation from the soil, resulting in higher interaction loads.

Research conducted by Dancygier and Karinski (1999a) focused on the effects of the loading function, specifically the loading period, and on load relief mechanisms. It was concluded that shorter impulse loads resulted in dynamic soil arching being the predominant mechanism of load relief, while longer impulsive loads resulted in static soil arching being the predominant mechanism of load relief.

Dancygier and Karinski (1999b) analyzed the effects of repetitive surface loads on buried structures. It was determined that deeper buried structures are more influenced by static soil arching and that repetitive surface loading can cause resonance conditions characterized by large amplifications of the interface structure deflection.

The effects of a soft overlying layer of soil in controlling soil arching above a soil were analyzed by Dancygier and Yankelersky (1996). The authors noted that in dynamic situations a soft layer can greatly reduce dynamic loads reaching and interacting with a buried structure by forming a reflective boundary due to the large differences in material impedance.

2.4 Summary

The leading humanitarian demining method is manual demining due to the effectiveness of the process, though this method is limited due to slow demining time and operator safety.

Mechanical demining is used in conjunction with manual demining operations to increase productivity and operator safety, Mechanical demining devices range from chain flail devices, tiller and roller systems and toolkit systems. Mechanical methods are severely hampered by knowledge and performance issues. The proper application of mechanical demining equipment has not been studied. The neutralization effectiveness of demining devices in the field has not been properly documented leading to under usage and poor neutralization results. There is also limited theoretical knowledge concerning the soil-tool interaction of demining devices. Current demining devices employed by demining organizations are hindered by a range of performance issues. Many devices employ high-technology components that are ill-suited for use in developing countries due to extreme operational and environmental conditions and a lack of a support infrastructure needed for transportation, in field maintenance and repair. Demining organizations are often poorly funded and cannot meet the cost of acquisition, operator training and high maintenance costs. The results of these negative attributes have led to a lack of acceptance in the demining community.

Recent research relating to the soil-tool interaction of demining mechanisms, such as chain flails has been initiated. The impact force due to impacting devices has been theorized to be a function relating to the speed, impact angle and the geometry of the impacting tool. Physical soil properties such as compaction greatly influence the magnitude of the impact force. Researchers have modeled the resulting pressure distribution due to impact using a modified version of the Boussinesq equation. There is no research relating to the actual interaction between a buried landmine and a pressure wave due to surface impact. Although an extension of research relating to the interaction between buried structures and pressure wave propagation through soil may be made.

CHAPTER III

DETERMINATION OF THE OPTIMAL SOLUTION

The following chapter focuses on the development of a mechanical demining device for antipersonnel landmines. The methods used in developing and refining potential designs follow an iterative approach involving (Spotts, 1998):

- **Concept generation:** A brainstorming session was used to generate potential ideas and simplified model development.
- **Parameterization:** Parameters for evaluating designs are developed, quantified and assigned relative weights in terms of importance.
- **Evaluation and elimination**: Design possibilities are evaluated according to a design matrix. The highest ranking designs are chosen for further evaluation.
- **Preliminary design testing:** Top ranked designs are tested and evaluated based on operational performance before a more detailed analysis with equipment alteration being addressed.

3.1 Concept Generation

A brainstorming session was used to produce a broad spectrum of possible concepts. The design goal of developing a mechanism for neutralizing AP landmines to depths of 200 mm was used to initiate the session. After the brainstorming process was completed and a set of design parameters were obtained, the concepts as generated were to be further analyzed. Parameters such as impact force and magnitude, impact frequency, power consumption and design simplicity were evaluated. These parameters served as an evaluation aid in a simplified design matrix. In many cases, even preliminary calculations regarding impact energy, power requirements and impact frequency were not developed due to obvious concept flaws. Many of the initial concepts were rejected on grounds of design feasibility and simplicity. Conceptual designs rejected and accepted are briefly described to represent the vast scope of the concepts and to provide a basis for future design investigations.

3.1.1 Rejected Design Concepts

3.1.1.1 Freefalling/Ballistic Impact Mechanism

Similar to using an automatic rifle or machine gun, rounds of high velocity projectiles of soil, biodegradable pellets or metallic objects could be fired to impact the surface. The projectiles would penetrate the soil and neutralize landmines by detonation and/or fragmentation. Potential propulsion energy sources for the ballistics include gravity, spring, hydraulic or pneumatic. Little to no physical constraints would be used on the object to isolate the impacting projectile from the rest of the machinery. Thus, in the event of landmine detonation, the impacting projectile is subjected to the blast force while the demining machinery would be at a distance from the explosion.

Since manual demining employing metal detectors, commonly follows a mechanical clearance method for quality assurance, using projectiles with metallic components would hamper the follow-up practices. The design was primarily rejected on the grounds of:

- an effective and reliable method of removing the ballistics from the ground complicates the design and had not been conceived;
- biodegradable or other non-metallic projectiles were not commercially available;
- in the event of a landmine detonation, the possibility of the ballistic could be thrown into adjacent areas and could adversely affect manual clearance efforts. Flying debris and projectiles inherently pose a risk for damaging the clearance machinery and a safety risk for machine operators; and
- the effects of vegetation in deflecting or preventing a projectile from delivering a surface impact are complex.

3.1.1.2 Hammer/Vegetation Cutter

Many chain flail demining machines have the ability to perform demining operations as well as vegetation cutting, but are limited to smaller tree sizes. A design incorporating a rotary impact system such as the Mine Hammer (Kushwaha *et al.*, 2004) with a chain based vegetation cutter was envisioned. The device would be composed of a central power shaft, and a series of mine hammers and vegetation cutting flail pairs. As the device traverses the terrain, the vegetation cutter would cut any dense brush/debris, as well as loosen the soil. The trailing hammers would impact the soil in an attempt to neutralize any landmines.

Currently, there are commercial machines in use that are designed for use as brush cutters, neutralization devices or both. Flail systems, most commonly used in clearance operations have been shown to perform well in debrushing operations (Dirscherl, 2003). Some brush cutting equipment, such as the Promac Brush Cutter (Burke *et al*., 2001), has been employed for demining applications as well. Other mechanical neutralization systems use a modular or toolbox approach in which a vegetation clearing system is used followed by a landmine clearing system, as is the case of the Tempest Mk V or the Armtrack 325 (GICHD, 2004). Due to the amount of commercially available machines, it was concluded that research focusing on a combined vegetation cutter and deminer would not provide any significantly new knowledge or innovative designs to the market. Also, a fully integrated vegetation cutter and deminer may not offer any real advantage. Some landmine machine researchers suggest a modular approach offers better possibilities (Dirscherl, 2003; Habib, 2002).

3.1.1.3 Rotational Disk with Inner Impacting Device and Moving Segments

Two similar concepts were identified and evaluated. A description of each concept (Concept 1 and Concept 2) is followed by an evaluation.

Concept 1

A large steel wheel is used to neutralize landmines, as illustrated in Figure 3.1. The static force due to its weight is applied at the surface along with a periodic force generated from sliding segments within the wheel. The outer part of the wheel is composed of a series of radial steel segments. Each segment, located along the outer diameter, is able to displace radially a finite amount. A device in the center of the wheel, possibly a cam or spring triggered mechanism, is used to deliver a strike to the inner surface of the steel segment as it contacts the ground. The segments act as a hammer which delivers an impulse to the soil surface. As the wheel rotates, a new segment comes in contact with the ground and the inner mechanism delivers the next impact. Thus, the system would apply a mean static load plus an additional impulse.

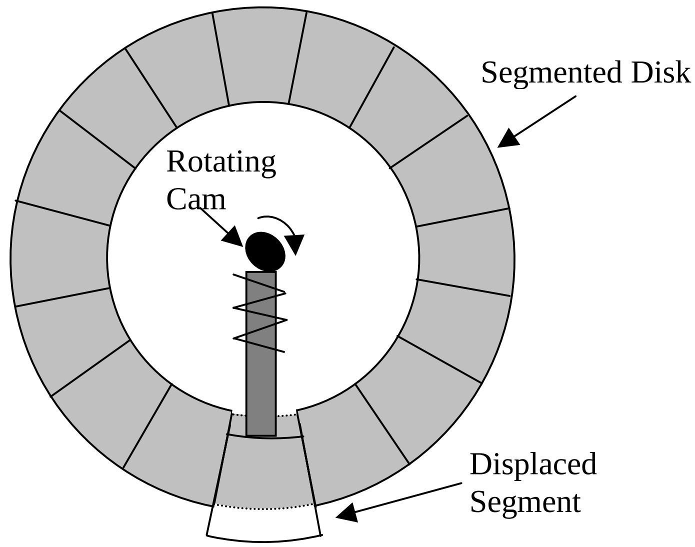

Figure 3.1 Schematic representation of an impacting roller with sliding segments.

Concept 2

A large diameter solid disk with radially, bored cylinders, as illustrated in Figure 3.2 is the basis for the second design. Inside each channel is a sliding mass. Each channel is partially covered, allowing a small portion of the inner mass to protrude when flush against the surface. As the disk is rolled over the ground, the masses in the channel slide around. The masses in channels pointing upwards slide towards the center. Masses in channels pointing downwards are held (possibly due to the geometry of the cylinders) until the channel is perpendicular to the ground. At this point, the masses are allowed to slide downwards, where a part of the mass protrudes from the disk, delivering a blow to the soil.

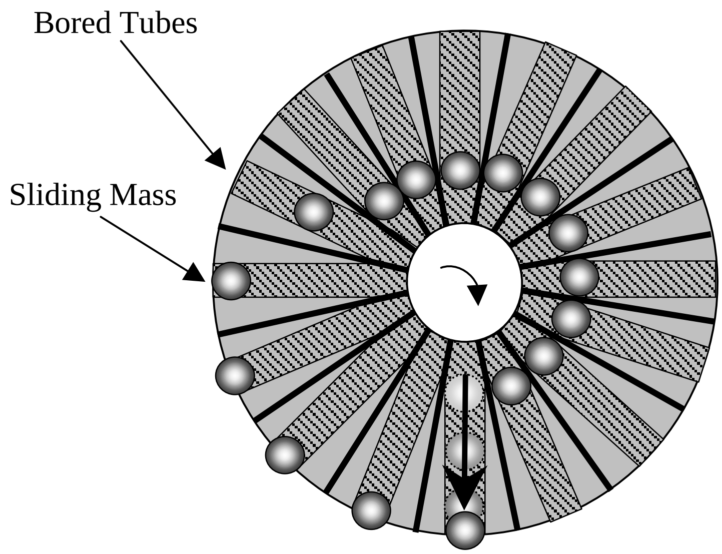

Figure 3.2 Schematic representation of an impacting roller with sliding mass.

Both designs were rejected mainly due to unnecessary design complexity. The wheel segments would likely need to be custom made and fitted which increases fabrication costs. The number of moving parts and sliding surfaces bring into question the durability of the mechanism and the mechanisms service life. The service environment, which may include local environmental conditions such as sand, mud or moisture, as well as effects from landmine detonation, would adversely affect the operation of the mechanism as the mechanism would be in direct contact with the surface and directly above potential landmine blasts. The impact frequency would also be lower than desired, unless large diameter wheels are used. A larger wheel diameter creates problems such as limited ability to follow terrain changes, lower ground surface forces due to larger contact area and larger power requirements for the prime mover to move the wheel.

3.1.1.4 Segmented Rollers with Springs

Similar to segmented disk rollers (such as the Pearson Area Reduction Roller currently available (GICHD, 2004)), the design would incorporate free rotating, segmented, metal disks. A portion of the prime mover mass would be supported by the rollers. Inside the rollers, compression springs would be used to apply a constant force in a downward direction on the bottom inner surface of each disk increasing the mean surface load. There were no obvious advantages to this design. The extra force due to the springs could be delivered using heavier rollers. There are no constant force compression springs, thus, terrain that undulates the springs compress more, resulting in more force on high ground, while the applied force decreases if the terrain height drops.

3.1.1.5 Two Stage Impacting Device

An impacting tool comprising of a two stage impact mechanism was considered. The first stage delivers a force capable of detonating a landmine. The second stage would be used to fragment any landmines that are only partially neutralized. The conceptualized design involves a vertical cylinder approximately 0.1 m in diameter with one or more holes bored in the middle. A second cylinder(s) would fit inside this cylinder, with a smaller impact surface diameter. As seen in Figure 3.3, during the first stage of impact, the ends of both the inner and outer cylinders are used to impact the ground. As seen in Figure 3.4, during the second stage, the inner cylinder is propelled further, delivering an additional impulse capable of neutralizing a landmine. The driving mechanism would involve a series of springs or cam systems.

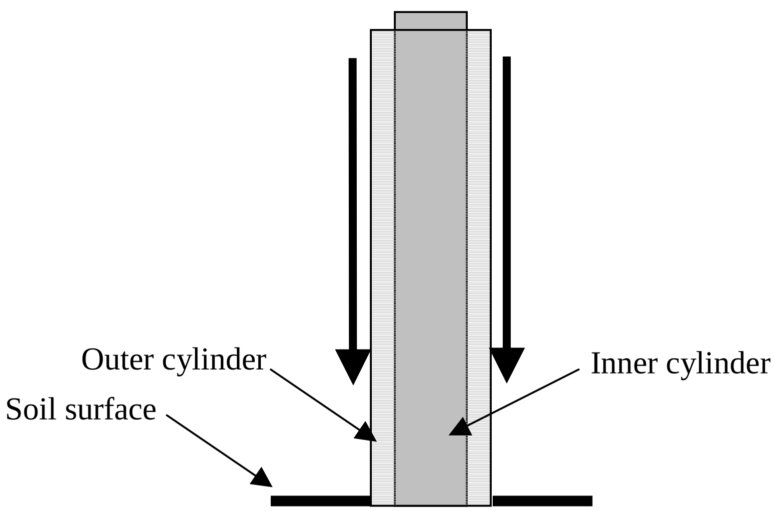

Figure 3.3 Schematic representation of the first stage of impact, where both inner and outer cylinders impact the ground.

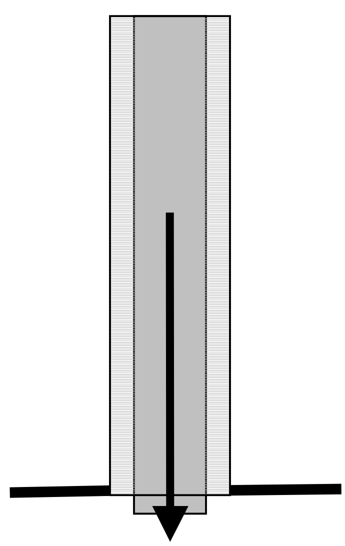

Figure 3.4 Schematic representations of the second stage of impact, where the inner cylinder delivers an additional impact.

The design was rejected primarily because it does not offer any real advantage over current impact tools. Devices such as chain flails and tillers are effective in neutralizing landmines using simple concepts with a single impact. A two stage impact device would be far more complex. The energy needed to further penetrate the soil for the second stage conceivably would be greater than that of the first stage. A design focusing the impact energy into one strike conceivably would be much simpler and effective.

3.1.1.6 Roller/Jackhammer Tool

Two similar concepts were identified and evaluated, as presented below as Concept 1 and Concept 2.

Concept 1

Concept 1 is a rotating disk simply supported by bearings on a central axle. At both ends of the axle are links attached to either a jackhammer or crankshaft device. The jackhammer would be used to deliver an impulse to the axle and wheel. In essence, the wheel and bearing assembly would be the impacting interface of the jackhammer. The sliding crank is similar, except the slider would push the wheel up and down, penetrating the soil and delivering a repeatable impact as the disk rolled. The disks would be used in a modular approach with 5 or 6 disks separating the mechanisms.

Concept 2

A second concept involves a series of segmented disks on a common shaft that are rolled along the ground, similar to the Pearson Area Reduction Roller (GIHDC, 2000). A jackhammer/slider-crank mechanism is used to deliver a periodic vertical impulse force on the ends of the common axle, which is transferred to the segmented disks and to the ground.

The major disadvantage lies in the loading of the axle bearings. Acquiring an inexpensive bearing capable of surviving an impact frequency and magnitude for an acceptable service life was doubtful. For the same reasons, the impact between the axle and segmented disk may have a limited service life. Also, the large variation of disk positions along the axle and the effective force/impulse transfer form axle to disks was questionable in its efficiency.

3.1.2 Further Development of Conceptualized designs

Upon completion of the initial brainstorming session, a series of possible design concepts with various configurations were identified for further investigation and analysis. In many cases, the concepts were extensions of the initially evaluated concepts, yet in their commercialized form. Commercial, off-the-shelf equipment was chosen for use, due to accessibility of the equipment and potential low cost for the end user.

3.1.2.1 Accepted Design Concepts

3.1.2.1.1 Dropping Mass Mechanism

A series of masses are dropped from a height to deliver an impact to the ground. The masses are raised using pulleys or a crank mechanism. On impact, the mass transfers its kinetic energy to the soil. Landmines are neutralized by detonation or fragmentation.

The dropping mass device was chosen for further analysis due to its simplicity, adaptability and commercially available designs. Commonly found designs, such as pile drivers or fence post drivers use simple technology and parts. The drop height and/or mass can be adjusted to vary the impact force to suit different soils and terrain. Impact frequency may also be varied in a similar manner.

3.1.2.1.2 Slider-Crank Mechanism

A design based on a slider crank mechanism delivers repeated blows to the earth. The slider crank is a common mechanism used to translate rotary motion into a reciprocating linear motion. The mechanism is composed of a crank, a connecting rod and a slider. As the crank turns around a fixed axis, the motion is translated to the connecting rod which can freely rotate about pins located at each end. The connecting rod pushes the slider, which can move along a fixed axis. As the crank completes the turn, the slider reverses its motion.

This device was chosen for further analysis due to design advantages such as simplicity and versatility. The slider crank is a simple mechanism used in many devices such as compressors and automobile engines. The frequency of impact can be varied by changing the rotary speed of the crank, and the force and displacement varied by changing the lengths of the crank arm, connection rod and end mass.

3.1.2.2 Commercial Design

3.1.2.2.1 Pile Driver

A commercial realization of the dropping mass mechanism includes pile drivers. Pile drivers are used for construction and agricultural applications to drive piles or posts deep into the ground. The basic operation of a pile driver involves a falling mass being repeatedly dropped onto a post or pile which generates a large, constant impact force. The mass can be lifted in a variety of methods, including using cables, hydraulic actuators or diesel powered sources, or combinations of power sources and wires. Similarly, for landmine clearance, a large mass can be repeatedly raised and dropped onto the ground. The resulting impulse upon impact would detonate or fragment landmines. The weight and size of the mass is dependent on the drop height and the contact or impact surface (i.e., pressure).

A design based on a pile driver (dropping mass) concept was chosen for further assessment, based on potential impact energy, flexibility, simplicity of design, durability and commercial availability. The amount of impact energy produced from a large falling mass is significant. Large industrial pile drivers typically supply over 40,000 J of impact energy. Smaller pile drivers are used for driving fence posts and supply over 2000 J of impact energy. Design flexibility exists since the impact energy can be adjusted by changing the drop height. A dropping mass mechanism can conform to changing or undulating terrain. The pile driver concept has been in use in various forms for many years with a variety of commercially produced pile drivers existing. The complete mechanism is a relatively simple design – a dropping mass and a system to elevate the mass. Repairs and maintenance can be easily performed based on accessible parts and technology. The design was considered fairly durable since large masses can more easily withstand and absorb the explosion from landmines.

3.1.2.2.2 Impact Hammer (Jackhammer)

Similar in concept to the pile driver, a mass is repeatedly accelerated downward, where it impacts a hammer. The energy from the accelerated mass is transferred to a hammer, which impacts the ground. Springs and cam systems are used to accelerate the mass, while electricity, pneumatics and hydraulics are used as power sources. Jackhammers, a common type of impact hammer, are used for various applications, specifically concrete cutting and demolition, tamping and post driving.

The jackhammer concept was chosen for further analysis due to many positive features including high impact energies, high impact rates, a range of available commercial products, modular possibilities and high durability. Depending on the size, jackhammers can provide between 50 to several thousand joules (J) of impact energy at over 15 beats per second (bps). Commercially, sizes range from small hand-held hammers to larger, more powerful hammers that are mounted on prime movers. Jackhammers are marketed globally. Due to the nature of its use, it was foreseeable that the hammers would withstand abusive and extreme environments. Furthermore, the hammers have the potential to be used in modular, self-contained designs.

3.1.2.2.3 Rammer/Tamper

Tampers are hand-held devices typically used for soil compaction in construction. Tampers use a slider crank mechanism coupled with internal springs to ‘bounce’ on the surface of the soil. As the tamper bounds along the soil, soil is compacted due to the impact between the soil and tamper foot. The mechanism is typically powered by a gas or diesel engine.

The tamper was chosen for further analysis due to its ability to produce substantial impact forces, design simplicity, its availability and versatility. Tampers can apply over 80 J of impact energy at 14 bps. The simple design and availability of the product allows for easy maintenance and accessible replacement parts. Tampers are predominantly used in industrial environments, thus, durability is inherent in the design.

3.1.2.2.4 Vibratory Rollers

Vibratory rollers are primarily used in construction for compacting loose or disturbed soil. Compaction is achieved using a combination of weight and impact force of the contacting roller. The impact force and its vibrations are induced within the roller by means of rotating eccentric masses. The magnitude of the impact force is a function of the vibration amplitude and frequency.

A design based on a vibratory roller was chosen for further assessment, based on impact frequency, flexibility of design, durability and commercial availability. Though vibratory rollers have a relatively low impact energy (less than 100 J) and resulting displacement, they do have the advantage of high impact frequencies (> 30 bps). For many designs, the amplitude and frequency can be adjusted to match the medium being compacted (MBW Inc., 2004). There is a large variety of commercial designs and sizes available for different applications. Smaller rollers can be boom mounted or pushed, while larger roller widths are self-propelled. The interface surface of rollers comes in various configurations, such as sheep's foot or smooth. The sheep's foot drum concentrates the static and dynamic weight of the roller on a small area (MBW Inc., 2004). The rollers are composed of thick steel, thus the weight and structural strength may be sufficient to withstand AP landmine blasts.

3.2 Design Parameters and Method of Evaluation

A set of design parameters were developed to serve as the evaluation tool of the conceptualized designs identified in Section *3.1 Concept Generation*. Current evaluation protocols and the cataloging of available landmine clearance machines served as a guideline for formulating the list of both operational and performance based parameters (Coley, 2002a; Coley, 2002b; Coley, 2003; GIHCD, 2002; GIHCD, 2004a; GIHCD, 2004b; GIHCD, 2005).

3.2.1 Design Parameters

3.2.1.1 Impact Force/Energy Comparison

The force transmitted to and through the ground upon impact is dependent on a complex interaction among the impact force, depth of tool penetration, stopping time and soil characteristics, such as composition and stress history (Shankhla, 2000). For the preliminary design analysis, it was not plausible to determine the momentum and resulting force transmitted to the ground upon impact, due to a lack of design data and variability in operating and soil conditions. A more general method of comparison was to assess the impact energy by calculating the kinetic energy (*KE*) of the tool before soil impact. The kinetic energy of tool is a function of its mass and velocity, as given by the equation:

$$KE = \frac{1}{2} m v^2 + \frac{1}{2} I_r \omega^2 \tag{3.1}$$

where

KE = kinetic energy (J),

m = mass of impacting tool (kg),

v = velocity (m/s),

I_r = moment of inertia (kg-m^2)

and ω = angular velocity (rad/s).

Due to limited data on the kinetic energy of impacting tools, the kinetic energy of various chain flails was used as a basis of comparison. There is a large variability in end mass configurations and in many cases; the end mass configuration is not stated. Thus, an end mass of 1 kg was assumed. Using a range of averaged values for the tabulated data as reviewed in the literature, a range of *KE* values can be calculated. For example, the mini-flail, Diana 40T (HONTstav Ltd., 2004) which boasts a 4000 N ground strike energy, creates 641 J of impact energy with m = 1 kg, ω = 600 rpm, and R = 0.57 m.

The main thesis objective was for a design capable of creating enough impact force to detonate an AP landmine 0.2 m below the soil surface. A design producing little impact energy does not fulfill this objective, even if other objectives such as cost, simplicity and maintenance are fully realized. Designs were evaluated on the amount of impact energy produced. The scoring chart used is presented in Table 3.1 with a median value of 600 J.

Table 3.1 Impact energy scoring chart.

Impact Energy (J)	Score
1000 and greater	5
800-1000	4
600-800	3
400-600	2
200-400	1
0-200	0

3.2.1.2 Impact Frequency and Forward Travel Speed

The forward speed of a mechanical clearance device directly affects neutralization effectiveness in a demining operation. A faster forward speed results in more area cleared, increasing productivity and cost effectiveness. However, faster forward speeds can adversely affect neutralization effectiveness in impacting and rolling clearance devices and depending on the impact frequency, a larger forward speed can result in skip zones due to the distance between impact strikes (GICHD, 2004b). If the distance between impacts is too great, a landmine may be missed. A different scenario is present for mines buried beneath the soil. As an impacting tool travels across the ground, a series of impacts creates a zone of influence. Landmines within the zone of influence experience sufficient pressure to be neutralized. The intensity of the pressure depends on the mines location with respect to the impact and the impact energy delivered. Landmines in the outer diameter of the influence zone experience lower pressure intensity (Shankhla, 2000) and may have a smaller possibility of being neutralized. Intuitively, closely spaced surface impacts should be more effective in neutralizing landmines at depth. Determining the optimal distance between strikes involves modeling the complex soil-tool impact interaction and the soil-landmine interface which currently has not been reported in literature. In the GICHD (GICHD, 2004b) study of mechanical application in demining, the authors noted that operators of the Armtrack 100 flail observed that the forward speed of flail systems affects the way a landmine has been neutralized. It was reported that a slower speed increased the fragmentation of mines, whereas faster linear speeds increased detonation of landmines. Although travel speed and impact frequency are closely related, the use of impact frequency was selected as a superior evaluation parameter because a higher impact frequency could result in a larger forward travel speed while maintaining a set distance between impacts. The impact frequency values used for the evaluation chart, as presented in Table 3.2, are based on averaged forward speeds found in the GICHD Demining Equipment Catalogue 2004 (GICHD, 2004c), with a median value of 13 bps.

For designs implementing a continuous rolling mechanism, such as tiller systems and rollers, the forward travel speed of the tool will be used instead of impact frequency. The weighted value of the forward travel speed evaluation criteria will be the same as the impact frequency criteria. Forward travel speed values used for the evaluation chart are based on averaged forward speeds found in the GICHD Demining Equipment Catalogue 2004 (GICHD, 2004b), with a median value of 0.15 m/s, as shown in Table 3.2.

Table 3.2 Impact frequency and forward travel speed scoring chart.

Impact Frequency (bps)	Forward Travel Speed (m/s)	Score
25 and greater	0.20 and greater	4
15-25	0.15-0.20	3
10-15	0.10-0.15	2
5-10	0.05-0.10	1
0-5	0-0.05	0

3.2.1.3 Design Power Requirements

The design power requirements include both the power needed to drive the mechanism and power needed to move the system. Large power requirement designs involve large, massive power generation equipment which increases the power needed to move the system. Many authorities believe that at least 52 to 60 kW/m is needed for effective landmine neutralization, although this value has not been tested or proven (GICHD, 2004b). Based on limited technical specifications from the GICHD Demining Equipment Catalogue 2004 (GICHD, 2004c), the average power per unit meter was 49.5 kW. Tiller systems have much higher power requirements due to the increased machine weight and the neutralization technique, though no specific data concerning power per unit meter was found. Thus, as a basis of comparison, the power per unit meter of flail systems was used for scoring, with a medium value between 45 to 52 kW/m, as shown in Table 3.3.

The weight of a design affects the power requirements for mobility. Heavier systems, such as tillers, require large, powerful engines to power the tiller drum and the prime mover. Large, massive prime movers have many adverse effects, including environmental effects of soil compaction, mobility and transportation problems. Thus, a design with minimal power requirements and mass has a definite advantage. To evaluate the effects of the design mass on power requirements, a power to mass ratio value corresponding to 2.7 kW/t was chosen to aid in comparisons. The value of 2.7 kW/t was stated by the GICHD (GICHD, 2004c) as being a design parameter automotive engineers use to ensure vehicle mobility for on and off road applications. The weight of the clearance units of tillers and flail systems ranges from 0.75 to 5 t. For evaluation, a median value of 6 kW was used in the scoring chart shown in Table 3.3.

Table 3.3 Power requirements scoring chart.

Clearing Power (kW/m)	Moving Power (kW)	Score
0-37.3	0-2	5
44.7-37.3	2-6	4
44.7-52.1	4-6	3
52.1-59.7	6-8	2
67.1-59.7	8-10	1
67.1 and greater	10 and greater	0

3.2.1.4 Design Flexibility and Performance

A demining unit will be subject to a multitude of terrains and environments. Studies indicate that machines are severely limited by terrain and weather conditions present in a given mine field (Tariq, 1998; GICHD 2004b). Steker (2003), of the CROMAC Center for Testing, Development and Training, stated that the design goal is to “develop a machine that will be fully efficient in different conditions”. A machine capable of being effective in multiple environments is a definite asset. Also, knowledge concerning the effectiveness and proper application of demining units to specific environments is limited (Kaminski, *et al.,* 2003; Dirscheral, 2003; GICHD, 2004c; Maki, 2002).

Often the strike pattern defines the machines effectiveness. If a strike pattern results in missed soil (skip zones), functioning landmines may be left. Overlapping strike patterns increase the chances of neutralization and improve the clearance efficiency. The strike pattern is a function of the impact frequency and travel speed. Overlapping strikes can be achieved with a high impact rate and slower travel speed.

The environmental performance and strike pattern of designs are evaluated on a range of possible terrains, including vegetation, rocky soil, sloping terrain, undulating terrain, dry and wet soil, as well as strike pattern. Each was evaluated separately and allotted a maximum value of 3 for very good performance and 0 points for insufficient performance.

Full neutralization of a landmine can be accomplished by detonation or mine fragmentation. Both have positive and negative repercussions. Detonation of landmines effectively neutralizes and eliminates the risk *in situ*. Detonation is also useful in area reduction operations, where a detonated landmine indicates the presence of landmines in the area. If a landmine contains metallic fragments, when detonated these may be projected into adjacent areas. The presence of metallic particles severely impedes the efficiency of manual demining operations (Tariq, 1998; GICHD, 2004b) which is an integral part of mechanical demining (Barrett, 1997). The environmental and health effects of landmine detonation have not been thoroughly analyzed. It is known that the explosive components of landmines, such as 2,4,6-trinitrotoluene (TNT), enter the environment through landmine detonation, where toxic gases and particles enter the atmosphere and contaminate soil and water. Civilians can be exposed to contamination through ingestion of contaminated water and plants grown on contaminated soil (ATSDR, 1995). As stated from the ATSDR ToxFAQ website (1995), the health effects of humans exposed to TNT include anemia, abnormal liver functions and immune systems effects. TNT has also been listed as a possible carcinogen. Incomplete detonation of landmines can also arise. On occasion, the fuse of a landmine will be detonated, but the main charge remains intact. Such landmines are termed ‘partials’ and are still considered hazardous (GICHD, 2004b). Though there is no standard definition for a fully neutralized fragmented landmine (Griffiths and Kaminski, 2003), the fragmentation of landmines can result in full neutralization (GICHD, 2004b). Fragmentation of the landmine has the potential of neutralizing the landmine in cases of improperly placed landmines or in regions where soil erosion or shifting has occurred. In the “GICHD Study of Mechanical Application in Demining” (GICHD, 2004b) the authors report that dog handlers of the demining organization RONCO preferred mine fragmentation to detonation, as detonation causes land contamination of the surrounding area.

Due to the consequences of either forms of neutralization, knowledge concerning the desired clearance application, such as area reduction or clearance followed by manual methods must be factored in when evaluating designs. Since present designs are general in nature and knowledge of the specific applications was unknown, no evaluation related to the type of neutralization that the mechanism achieves was made. Furthermore, the same mechanism under varying environmental or operating conditions may be capable of achieving both or predominately one type of neutralization (fragmentation and/or detonation).

3.2.1.5 Soil Effects

Demining devices such as flail and tiller systems tend to leave a subsoil layer of hard, compacted soil, called a hardpan. The hardpan can create various problems for further demining operations as well as future land use. During a mechanical demining operation, functional landmines can become impacted in or below the hard sub-layer, effectively isolating the landmine from mechanical neutralization methods. The impacted landmines also create additional hazards for manual demining and quality assurance operations, where deminers have increased difficulty locating and removing the landmines (GICHD, 2004b). The majority of landmine contaminated areas are found in developing countries, where agriculture is the main usage of land (GICHD, 2002). Thus, soil compaction is a concern. The agricultural effects of soil compaction include poor crop stands, irregular growth of plants and insufficient drainage causing wet soil (Canillas *et al.,* 2002). A study conducted by the GICHD entitled ‘Mine Action Equipment: A Study of Global Operation Needs’ (GICHD, 2002) states “there is an obligation for mine action programs to maintain the integrity of contaminated land as a source of food and livelihood for the local population”.

Many clearance machines, including flail and tiller systems create a cover of loose soil or overburden. The effects of overburden include the burying and concealing of landmines, increasing quality assurance process times and effectiveness as well as shielding landmines and UXO from detection from metal detectors and other sensors (GICHD, 2004b). The presence of dust clouds produced from the impact of tool can cause visibility problems for the machine operator, resulting in slower clearance and possible missed areas (GICHD, 2004). As in the case of flail systems and tillers, a machine producing flying debris due to the impacting action may result in ‘throw outs’ (GICHD, 2004b; Shankhla, 2000; Dirscherl, 2003; Leach, 2001; Leach, 2002) in which live mines or partially fragmentized mines and metallic particles are thrown out into adjoining areas, resulting in increased quality assurance process time if the area has been previously cleared, and increased hazardous conditions for manual demining operations.

Design concepts that have limited effects on land integrity and soil displacement were designated as superior designs. Designs were evaluated on the level of compaction and furrow effects. Each was evaluated separately and allotted a maximum value of 3 for low compaction/furrow creation, and 0 points for large compaction/furrow creation. It was noted that the evaluation may be fairly subjective.

3.2.1.6 Design Simplicity and Maintenance

Many reports from demining organizations indicate that the use of advanced technology, complex and expensive mechanical demining equipment is not suitable for most demining applications, especially in developing countries (Tariq, 1998; Dirscherl, 2003; Habib, 2002; Handicap International Mines Co-ordination Unit, 2000). Many of the mine afflicted countries are developing countries that cannot afford this type of equipment

(Tariq, 1998). Mechanical demining equipment is subjected to extreme operating conditions such as weather, terrain and landmine blasts, resulting in high wear and tear, limiting the use of many high technological options (Tariq, 1998). Maintenance personnel and equipment operators in such countries have minimal formal educations and the technology infrastructure needed to repair and service the equipment is poor to non-existent (Habib, 2002). In many situations, specialized equipment parts requiring machining or fabrication are not appropriate for on-field applications. Availability of off-the-shelf parts increases maintenance effectiveness and decreases costs (Dirscherl, 2003). When cost effectiveness is an issue, demining machines must operate continually with minimal servicing requirements. Some of the most successful and accepted demining machines have been adapted from commercial off-the-shelf parts or retro-fitted agriculture/forestry equipment (GPC International, 2002; Handicap International Mines Co-ordination Unit, 2000; GICHD, 2002; Hess, 1999). It has been noted that modular designs based on low cost and low technology have made large contributions to mechanical demining technology (Burke *et al*., 2003; Handicap International Mines Co-ordination Unit, 2000).

Maintenance of many mechanical demining machines is of prime importance and tends to be based on design simplicity. Impact tools such as chain flails and tillers require high amounts of maintenance and part replacement (Habib, 2002). Many conventional flail systems have been taken out of operation due to a lack of part availability and maintenance issues (Coley, 2002). An often stated factor contributing to the success of mechanical demining machines involves ease in repair of machines with a minimal amount of cost and time (Hess, 1999) as well as the ability to be repaired and maintained on site (Dirscherl, 2003).

Design simplicity and maintenance was evaluated based on modular design, availability of spare and replacement parts, manufacturing and fabrication ease, replacement part interchangeability, level of technology, and whether the technology has been proven. Parameters were scored on a basis of 1 to 3, value of 3 for very good performance and 0 points for insufficient performance.

3.2.1.7 Durability and Strength

A device used for mechanical demining must be able to operate in hostile conditions and withstand multiple blasts from AP landmines without suffering severe component damage (Habib, 2002). Commercial clearance machines were evaluated using a series of tests where the demining tool and demining vehicle are subjected to blasts from various amounts of explosive charges to evaluate the designs strengths (GICHD, 2004b). A contributing factor to the high maintenance costs is the general maintenance and replacement of parts, such as flails, hammers, teeth and chisels from general wear and tear (Habib, 2002; GICHD, 2004).

Design simplicity was evaluated based on the ability to withstand operating environments, the ability of withstanding blasts from AP and/or AT landmines, and the projected life of the designs components. Parameters were scored on a basis of 1 to 3, a value of 3 for very good performance and 0 for insufficient performance.

3.2.1.8 Costs

Problems of funding often limit many demining organizations to perform demining operations (Tariq, 1998; Habib, 2002). For machines to be of use, the cost of clearing one square meter of a mined area must be lower than traditional methods such as manual deminers and/or dogs (Dirscherl, 2003). Among many factors, the success of a machine depends heavily on the cost effectiveness of the design (Habib, 2002). The cost effectiveness of a machine is dependent on many factors, including but not limited to, power requirements, design performance, maintenance, durability, fabrication and/or acquisition costs and operator training.

It was not possible to quantify the costs associated with fabrication, acquisition or cost effectiveness of devices due to insufficient knowledge. Thus, the total cost of a design was evaluated on the resulting evaluation scores for the following parameters; power requirements, design performance, maintenance, durability, and fabrication and/or acquisition costs. A paired analysis was used to determine the weight of each relevant parameter. The score assigned to the total cost was then calculated by multiplying weights for each parameter by its score and summing the results. The evaluation parameters kinetic energy and impact frequency were not included in the paired analysis as they were deemed independent of cost effectiveness. Refer to Appendix B, Table B.2 for the paired comparison matrix used for the cost evaluation parameter.

3.3 Design Evaluation

A design matrix, as outlined in *The Mechanical Design Process* (Ullman, 2003) was constructed using the previously discussed evaluation parameters to assess the preliminary design concepts. A sample of the design matrix for a fence post driver is presented in Table 3.4. Details for each design matrix used are found in Appendix B, Tables B.3, B.5 and B.7.

Table 3.4 Design matrix sample for a fence post driver.

Design Parameter	Weight	Parameter Score	Weighted Score (Weight x Score)
Kinetic Energy	13.9	4/5	11.11
Impact Frequency	13.9	0/4	0.00
Power Requirements	8.3	8/10	6.67
Design Flexibility and Performance	19.4	10/24	8.10
Soil Effects	2.8	3/6	1.39
Design Simplicity and Maintenance	13.9	10.5/18	4.05
Durability and Strength	22.2	7/12	12.96
Cost	5.6	(n/a)	2.61
Score	(n/a)	(n/a)	46.9

The first column of the matrix consists of the evaluation parameters. The second column shows the weights associated with the parameter. The weight of each evaluation parameter was determined using a paired comparison technique. Details concerning the determination of parameter weights are found in Appendix B, Tables B.1, B.2, B.4, and B.6. The paired comparison technique comprises of listing the parameters along a vertical and horizontal axis; with the horizontal axis being the reference parameter. Parameters were compared individually for each combination. If the reference parameter was more important than the comparison parameter, a ‘1’ was placed in the corresponding cell. Conversely, if it was less important, a ‘0’ was placed in the cell. The sum of each horizontal row was obtained and divided by the total of each row's sum, resulting in a weighed value for each parameter. The score of each parameter was entered in the third column of Table 3.4. The weighted score of a parameter was achieved by multiplying the parameter score by its weight, as shown in fourth column of Table 3.4. The final design score was achieved by summing each value in the last column.

3.3.2 Design Matrix Results

A total of five (5) possible off-the-shelf devices were evaluated using the design matrix. The paired comparison and design matrix used are shown in Table B.1, Table B.2 and Table B.3 of Appendix B. A comparison to existing and proven technology for mine neutralization, the Pearson Area Reduction Roller and the Aardvark flail system was made. The evaluated mechanism included:

- a fence post driver;
- a diesel pile driver;
- a jackhammer;
- a tamper;
- a vibratory roller;
- a Pearson Area Reduction Roller; and
- an Aardvark M5 Flail.

During the evaluation, the assessment process inevitably became subjective because objective or quantified data for many of the design parameters, such as costs, maintenance, design flexibility and durability were not available. Comments by experienced operators were used when available to evaluate these parameters; otherwise, engineering intuition was applied. The final assessment also involved similar assumption to be made regarding some of the parameters.

3.3.2.1 Pile Driver

Two extremes of the pile driver mechanism were evaluated. The first was an industrial sized diesel pile driver, and the other, a small fence post driver.

3.3.2.1.1 Diesel Pile Driver

The industrial sized pile driver analyzed was based on a small single acting diesel hammer. Specifically, the model assessed was an APE model D1 diesel hammer (American Pile Driving Equipment Inc., Kent, WA). The total score for the diesel pile driver was a 51.3% as derived in Table 3.5.

Table 3.5 Evaluation parameter scores for the diesel pile driver.

Parameter	Parameter Score	Comments
Kinetic Energy	4/5	A large amount of kinetic energy was easily attainable, reaching minimum levels above 950 J even with smaller systems.
Impact Frequency	0/4	The large size of the pile drive significantly reduced its ability to provide a practical impact frequency, resulting in a maximum rate of 1.3 bps.
Power Requirements	5/10	The power requirements for the diesel pile driver were surprisingly low. Low power requirements may be due to incomplete data regarding the weight of the support tower.
Design Flexibility and Performance	10/24	The large size of the ram and impacting surface area, the need for a large support tower and the variability of the impact force due to environmental factors greatly affected the diesel pile drivers performance with respect to design flexibility.
Soil Effects	3/6	The impact of the design would result in large soil compaction with a possibility of furrow creation.
Design Simplicity and Maintenance	10.5/18	Due to the possibility of a modular design, the wide range of parts, and a fairly low level of technology, the diesel pile driver rated well.
Durability and Strength	7/12	Pile drivers are heavy duty equipment used in many environments including dusty, wet and marine environments. They are designed to withstand large impacts and deliver a significant force. Though the size and mass of the ram may be large enough to withstand blasts from AT mines, the support rig or engine may not.
Costs (fabrication & acquisition)	2.9/6	Based on Paired Comparison

3.3.2.1.2 *Fence Post Driver*

Fence post drivers are common tools used in agricultural applications for building and repairing fences for livestock containment. The model evaluated was a hydraulic powered drop hammer, called the Blackcat Post Pounder (Production Energy Services Inc., Inez, TX). The total score for the diesel pile driver was a 54.8% as described in Table 3.6.

Table 3.6 Evaluation parameter scores for the fence post driver.

Parameter	Parameter Score	Comments
Kinetic Energy	5/5	The fence post driver utilizes a heavy mass dropped at a specified, but variable drop height, resulting in the development of large impact energies in magnitude of 1400 J.
Impact Frequency	0/5	Due to the significant drop height needed and resulting power needs, the post driver was limited to a low impact rate of approximately 1.93 bps.
Power Requirements	8/10	The power requirements were found to be fairly low and comparable to the diesel pile driver. The low value may be primarily due to the low impact rate.
Design Flexibility and Performance	12.5/24	Inherent design characteristics of the post driver result in an average score for design flexibility. The design would not be suitable for rocky or slopping terrain, areas of high vegetation or wet or muddy conditions due to the prime mover attachment.
Soil Effects	4.5/6	Soil effects include soil compaction, but compaction effects may be limited by altering the drop height for different soil types. No soil furrow was expected.
Design Simplicity	11.5/18	The design of the fence post driver is based on simple and proven technology, and has modular capabilities.
Durability and Strength	5.5/12	Due to the mass of the drop hammer, it was expected that the mass will absorb much of a blast from an AP or AT mine. Questions remain about the capabilities of the support rig remain for both types if mines
Costs (fabrication & acquisition)	2.9/6	Based on Paired Comparison

3.3.2.2 Vibratory Roller

Vibratory rollers are commonly used in construction applications for compaction of soil in preparing foundations or road beds. Boom mounted rollers are used for trenches and other hard to reach areas. The model analyzed was an EXA boom mounted vibratory roller (MBW, Slinger, WI) with an 0.33 m wide interface width. The total score for the vibratory roller was 66.05% as detailed in Table 3.7.

Table 3.7 Evaluation parameter scores for the vibratory roller.

Parameter	Parameter Score	Comments
Kinetic Energy	0/5	Due to the small vibration amplitude of the vibratory roller, the device was able to produce only 3.6 J of impact energy. It was realized that the roller weight (2630 kg) would add a significant static weight.
Impact Frequency	4/4	The vibratory roller delivers a very high impact frequency of 43 bps.
Power Requirements	6/10	The power requirements for the roller were fairly low, with the majority being the needed hydraulic power.
Design Flexibility and Performance	4.5/6	Due to the intended use of the device, it was expected to perform well in varying soil and environmental conditions. The device is capable of applying a continuous and repeatable impact along the soil surface. Areas of concern include medium to high vegetation, rocky terrain, or highly undulating terrain.
Soil Effects	10.5/18	Presumably, the use of the roller will result in high soil compaction, though the effects may be minimized by altering the vibration frequency to suit soil types.
Design Simplicity	17/24	The technology used in the design is fairly simple (hydraulic motors used to rotate eccentric masses) and many types and manufacturers exist. The availability of spare or replacements parts may be an issue, due to specialty parts and part accessibility in different geographic locations.
Durability and Strength	10.5/12	Presumably, the large mass would help dampen the effects of blasts from AP and AT landmines to the supporting frame. The rollers are used in industrial settings, where dusty and wet environmental conditions are common.
Costs (fabrication & acquisition)	3.8/6	Based on Paired Comparison

3.3.2.3 Jackhammer

The model analyzed was a mounted hydraulic impact hammer/breaker used for demolition of concrete and rocks. The model evaluated was S 22/c (Sandvik Mining and Construction, Cleveland, OH). The total score of the jackhammer was 74.23 % as described in Table 3.8.

Table 3.8 Evaluation parameter scores for the jackhammer.

Parameter	Parameter Score	Comments
Kinetic Energy	1.5/5	As specified by the manufacturer, the unit was capable of delivering 280 J of impact energy.
Impact Frequency	3/4	The jackhammer was capable of deliver an average rate of 18.75 bps, which is common for most jackhammer models.
Power Requirements	6/10	The jackhammer power usage is average due to its smaller size. It was noted that an increase in input power greatly increases impact energy output.
Design Flexibility and Performance	22/24	The jackhammer design has the potential to perform very well in many environmental conditions, including areas of high vegetation, rocky, wet or dry soil, sloping or undulating terrain, while having the ability to apply a consistent and repeatable strike pattern.
Soil Effects	3.5/6	Soil compaction was an assumed result of usage, but this may be moderated by altering the hydraulic flow rates. Depending on the interface area, a small furrow may be created, though this is dependent on the initial soil compaction.
Design Simplicity	16/18	The jackhammer scored well in this section due to the possibility of a modular design and interchangeable parts, the high chance of replacement parts being available in many locales, and due to the fact that it was a simple device with proven technology.
Durability and Strength	10/12	Jackhammers are used in harsh environments ranging from dusty to wet conditions. The intended use is to break apart concrete and rocks, hence the hammers should be able to sufficiently withstand impacts from AP mines, and to a lesser extent AT mines.
Costs (fabrication & acquisition)	4.3/6	Based on Paired Comparison

3.3.2.4 Tamper/Rammer System

The model analyzed was LT800 Diesel powered tamper (Dynapac, Mississauga, ON). The tamper is used for medium soil compaction in construction applications. The total score for the system was a 59.5% as detailed below in Table 3.9.

Table 3.9 Evaluation parameter scores for the tamper system.

Parameter	Parameter Score	Comments
Kinetic Energy	0.5/5	Based on data provided by the manufacturer, as well as velocity and KE calculations, the impact energy of the tamper was determined to be 156.7 J.
Impact Frequency	2/4	Data from the manufacturer stated that the impact frequency is 12bps.
Power Requirements	10/10	The small size and use of a 2 stroke diesel engine resulted in low power requirements.
Design Flexibility and Performance	18/24	The tamper system rated high due to its estimated average to high performance in various soil conditions, and varying environmental situations such as rocky, sloping and undulating terrain.
Soil Effects	3/6	The tampers intended use is for medium soil compaction. Little to no furrow was expected.
Design Simplicity	9.2/18	The tamper can incorporate a modular design and is based on a simple (slider-cam) and proven technology. Tampers are widely used in the construction industry, thus spare parts are readily available.
Durability and Strength	7.5/12	The tamper system rated well with respect to durability in diverse operating conditions and projected component life. Due to the mass and construction of the tamper, it was expected that blasts from AP mines would not result in tool damage, but impacts from AT mines may not.
Costs (fabrication & acquisition)	3.8/6	Based on Paired Comparison

3.3.2.5 The Aardvark MK5

The Aardvark MK5, manufactured by Aardvark Clear Mine Ltd (Insch, Scotland) is one of the most used mechanical clearance machines used (GICHD, 2004c) and has been thoroughly tested. Thus, the MK5 was chosen to represent a common commercial device presently used in the demining community. The total score was calculated to be 67.9% as shown in Table 3.10.

Table 3.10 Evaluation parameter scores for the Aardvark MK5.

Parameter	Parameter Score	Comments
Kinetic Energy	3/5	Based on manufacturer specifications for chain length, speed and mass, the impact energy was estimated to be 765 J, resulting in an average score
Impact Frequency	3/4	The impact frequency was estimated to be 15.25 bps, based on the units maximum rotation speed
Power Requirements	9/10	The low mass and low energy requirements needed for the flail unit resulted in a high score
Design Flexibility and Performance	14/24	The Aardvark scored high to average in all areas except for rocky and wet terrain, as well as strike pattern and repeatability.
Soil Effects	3/6	A flail system causes tilling and dust clouds, resulting in an average score
Design Simplicity	12.5/12	The chains can be easily replaced, spare parts are available but must be shipped, there is operator and maintenance training, but maintenance can be done in the field. The technology is simple and the device field proven.
Durability and Strength	8.5/12	Due to the size and simplicity, the flail can operate in many conditions, but is limited to AP mines-but not as a primary demining and was assumed to have a good service life
Costs (fabrication & acquisition)	3.6/6	Based on Paired Comparison

3.3.2.6 The Pearson Area Reduction Roller system

Rollers have been used for demining situations, predominantly military, for many years, and have been adapted for humanitarian purposes. The Pearson Roller (Pearson

Engineering, Walker, England), shown in Figure 3.5, is a typical roller used in many humanitarian operations all over the world (Coley, 2003). The total score was calculated to be 54.2% as shown in Table 3.11.

Figure 3.5 The Pearson Area Reduction Roller[13].

Table 3.11 Evaluation parameter scores for the Pearson Area Reduction roller.

Parameter	Parameter Score	Comments
Kinetic Energy	0/5	Due to the mechanism of landmine detonation, there was none to little impact energy.
Forward Travel Speed	2/4	No data on operational speed was given by the manufacturer, but it has been found that the speed must be varied greatly, depending on the soil conditions. Thus, it was assumed that the roller would operate around 0.1-0.15m/s, resulting in an average score.
Power Requirements	9/10	The roller is pushed by a prime mover, and the weight/m is low to average, resulting in a very high score
Design Flexibility and Performance	14.5/24	The Pearson roller does not perform well in vegetation or rocky soil. Multiple passes is typically required for such areas and is not considered a realizable or repeatable device.
Soil Effects	2/6	The weight of the roller does cause soil compaction, but little soil disturbances has been observed.
Design Simplicity	15/18	In general, the Pearson roller is very simple modular design based on easily accessible spare parts, simple and proven technology.

[13] Photograph taken from Photograph reproduced from GICHD. 2004. Mechanical demining equipment catalogue 2004, Geneva, Switzerland: Geneva International Center for Humanitarian Demining, page125.

Durability and Strength	7/12	The roller can be used in most environmental conditions and has a long operational life, but was not considered a reliable demining mechanism (Heiss, 1999).
Costs (fabrication & acquisition)	3.5/6	Based on Paired Comparison

3.3.3 Design Matrix Results

The results of the design matrix evaluation are tabulated below in Table 3.12 in decreasing order of design rank.

Table 3.12 Design matrix evaluation results for the five off-the-shelf devices and two commercial mechanical demining devices.

Method	Score
Jackhammer	74.2
Aardvark Mk5	67.9
Vibratory Roller	66.1
Tamper/Rammer	59.5
Fence Post Driver	54.8
Pearson Roller	54.2
Diesel Pile Driver	51.3

The top four designs were

- Jackhammer,
- Aardvark MK4 Chain Flail,
- Vibratory Roller and
- Tamper/rammer.

Initially the top three designs (excluding the chain flail) were chosen for further testing and evaluation. In acquiring off-the-shelf mechanisms, a vibratory roller mechanism suitable for testing for the lab environment was not found. Thus, only the jackhammer and tamper were obtained for further testing.

3.4 Preliminary Device Testing

The initial device tests used rental equipment in its off-the-shelf format with experiments being conducted in the custom designed soil bin facilities, called the Terra Mechanics Rig (TMR) in the Department of Agricultural and Bioresource Engineering testing facilities, located at the University of Saskatchewan. The objective of the preliminary testing phase was to evaluate the effectiveness of the jackhammer and tamper devices for landmine neutralization before any equipment alteration and a more detailed analysis were to be completed. Primarily, the load and deflection of soil at various depths and soil compaction were assessed along with its ease of operation regarding maneuverability.

3.4.1 Apparatus and Procedure

3.4.1.1 Apparatus and Instrumentation

3.4.1.1.1 Soil Bin Facilities, TMR

The TMR test facility, shown below in Figure 3.6 is used for research on agricultural tools and soil-tool interactions. The TMR was re-engineered and designed in the Department of Agricultural and Bioresource Engineering and is located in the College of Engineering, University of Saskatchewan. The primary components of the TMR are a soil bin, carriage and soil processing tools. The soil bin is 0.76 m deep, 1.3 m long and 2 m wide. The carriage is hydraulically driven and is capable of supporting a variety of tillage tools and related instrumentation. The soil processing tools include a hydraulically driven rototiller, and rollers used for soil compaction.

Figure 3.6 The Terra Mechanics Rig.

3.4.1.1.2 Soil Parameters

Initial tests were performed in a clay-loam soil of approximately 47% sand, 24% silt and 29% clay. Moisture content of the soil varied between 10 to 20% and was measured used the oven drying method according to the ASTM: D2216 63T standard (ASAE, 2004).

3.4.1.1.3 Devices

The tamper used for the preliminary testing was a Wacker™ Model BS-50 gasoline engine powered Tamper (Wacker Construction Equipment AG, Munich, Germany)**,** shown in Figure 3.7. The jackhammer tested was a Bosch™ Brute electric jackhammer (Robert Bosch Corporation, Farmington Hills, MI), shown in Figure 3.8. Relevant specifications for each machine are presented in Table 3.13.

Figure 3.7 A Wacker™ gasoline engine powered tamper[14]

Figure 3.8 A Bosch™ Brute electric jackhammer

Table 3.13 Tamper and jackhammer physical and operational parameters.

Specification	Tamper	Jackhammer
Weight (kg)	58	30
Power (kW)	2.3	1.73
Impact frequency (bps)	11.7	24
Compacting interface (shoe) dimensions (m)	0.2 x 0.28	Shoe 1: 0.2 x 0.28 Shoe 2: 0.28 x 0.33

3.4.1.1.4 Load Cells

The two load cells used for the preliminary tests include a MassLoad Technology™ (Saskatoon, SK) shear beam load cell and an Interface Technologies™ (River Forest, IL) pancake load cell, shown in Figure 3.9. The load cells were used to measure the dynamic force transferred through the soil to different depths. The interface surfaces were designed with similar pressure interface areas of common landmines. The interface surfaces between the load cells and soil were increased using metal collars mounted on the load button of each cell. The collars were used to model the loading conditions seen by common landmines. The capacity of the Massload™ and Interface Technologies™ load cells was 8898 N and 2227 N, respectively. The excitation voltage of each load cell was specified at 110 V_{DC}. The output sensitivity for the Massload™ cells was rated at 1.783 mV/V and 2.156 mV/V for the Interface Technologies™ load cell. The interface

[14]Photograph reproduced from Wacker Construction Equipment AG , www.wackergroup.com

area of each sensor was 4.57×10^{-3} m^2. Each load cell was equipped with a 0.024×10^{-3} m^2 aluminum base plate to aid in sensor placement.

Figure 3.9 A Interface Technologies™ (River Forest, IL) pancake load cell.

3.4.1.1.5 Displacement Sensor

The displacement sensor used was constructed by the Department of Agricultural and Bioresource Engineering in the summer of 2003 (Laturnas *et al*., 2003), shown in Figure 3.10. The sensor uses a SS94A1B Hall Effect transducer to measure the vertical displacement of a top plate interfacing with the soil. The interface area and resistive force was similar to common AP landmines. The output sensitivity of the sensor was 1.87 mV/gauss with a range of ±500 gauss. The interface area of the sensor was $5.32 \times 10^{-3} m^2$. Details concerning the calibration of the sensor are found in Appendix C.

Figure 3.10 A displacement sensor used to measure the vertical displacement of a top plate interfacing with the soil.

3.4.1.1.6 Signal Conditioner

A 2300 System strain gauge conditioning amplifier™ (Vishay Americas, Shelton, CT) was used to condition and amplify the signals from the load cells and displacement sensor. A low pass RC filter was used to attenuate frequencies above 130 Hz.

3.4.1.1.7 Data Acquisition

The analog output signal from the signal conditioner was converted to a digital signal using a 12 bit AT-MIO-16F-5 plug-in digital A/D converter (National Instruments Corporation, Austin, TX). The A/D converter card was supported by the software LabView™ (National Instruments Corporation, Austin, TX), which allows a computer with an A/D board to be used as test equipment. The software can be programmed to display data similar to standard measuring equipment. All data was collected at 1000 Hz.

3.4.1.1.8 Cone Penetrometer

A cone penetrometer was used to measure the compaction of the top soil from the surface to depths of 0.30 m.

3.4.1.2 Procedure

The soil preparation procedure and sensor placement was completed as follows:

1. Soil was rototilled twice and leveled. Leveling the soil using the bar alone was ineffective as the bar floated on top of the soil. Thus, the rototiller was also used to aid in leveling the surface. The soil surface was manually sprayed with water when needed to maintain the moisture content.
2. Wooden planks were placed on the soil as walking paths to minimize soil disturbances.
3. A trench of approximately 1.5 m x 0.25 m x 0.3 m was dug for placing the load cells.
4. The bottom of the trench was lightly compacted by hand using a 0.1 m x 0.1 m x 0.3 m wooden block to a value of 100 to 150 kPa.

5. Each load cell was calibrated by placing a 22.7 kg mass upon the pressure sensing interfacing area and adjusting the signal conditioner gains as necessary on a rigid foundation prior to placing in the test lane.
6. Force transducers and the displacement sensor were placed within the trench at the prescribed depths. The sensors were spaced approximately 0.38 m apart. The location of each sensor was marked along the side wall of the soil bin and the trench was filled with removed dirt and the area was leveled manually.
7. The initial soil height with respect to the soil bin container was measured and recorded.
8. The initial compaction was taken adjacent to the sensor locations and recorded.
9. The tests were performed using three passes of the test equipment. After each pass, the force transferred to depth, the sensor displacement, the top soil displacement and soil compaction were measured and recorded.
10. After the three passes, the sensors were removed from the dirt, and the soil was roto-tilled. No repetitions of the test series was conducted due to time constraints.
11. Sensors were buried at 0.10 m, 0.15 m and 0.20 m depths per test series. Sensors were buried at 0.10 m, 0.15 m and 0.25 m depths for the Tamper.

3.4.2 Method of Analysis

The preliminary device tests will focus on the jackhammer and tamper mechanisms. The devices are compared using a secondary design matrix to evaluate the designs. As explained in Section *3.3 Design Evaluation,* a paired comparison was used to assign given weights to the respective evaluation parameters. Refer to Appendix B, Table B.5 for further details. Evaluation parameters used include the maximum relative sensor displacement, the maximum interaction pressure, the total impulse and the duty cycle. These parameters were chosen for evaluation purposes as they were objective and scientifically quantifiable.

A second design matrix was used to evaluate and compare the devices. A paired comparison was used to assign weighted values to each parameter. The device scoring the highest score was chosen for the final testing phase.

3.4.2.1 Parameter Summary

Each evaluation parameter is described whereby the assumption regarding a parameter, an argument supporting the assumption and the method of application are presented. The mathematics and data analysis software Matlab® (The Mathworks Inc., Natick, MA) was used to calculate the evaluation parameters. The methods and algorithms used are presented in Appendix D.

3.4.2.1.1 Interaction Pressure

A device capable of transmitting the largest possible pressure to a buried sensor has the greatest chance of actuating or neutralizing a landmine. Common AP landmine function on the premises of a load applied to a pressure sensing system, usually composed of a spring or diaphragm system, causing a physical deflection of the spring mechanism, which releases the firing mechanism. The static load needed to trigger common AP landmines range from 19 to 250 N (Canadian Forces, 2004). A review of current literature indicates that actual magnitudes vary from source to source. Also, in real situations, higher forces may be required due to landmine degradation from age, environmental and manufacturing variability. An applied force below the needed threshold will not cause adequate deflection resulting in an undetonated landmine. Thus, a tool capable of providing the largest force is the best design. Quantifying the actual force as seen by a landmine buried in the soil using sensors such as load cells, pressure sensors or displacement sensors is a complicated process. The forces detected by a load cell or other soil stress measurement device represent force present due to the interaction between the sensor and the incoming pressure wave. The forces as seen by a load cell do not represent the force as seen by a landmine, but measure a relative magnitude that can be compared between devices tested using similar testing methods.

Peak interaction pressures were compared between the tamper and jackhammer. The tool producing a larger magnitude force is deemed a better design. Due to a variation among landmine pressure sensing interfaces, the interaction pressure was used. The evaluation scores used, shown in Table 3.14, are based on test data performed by the author in the Department of Agricultural and Bioresource Engineering, University of Saskatchewan, on two deactivated PMN antipersonnel landmines. Details concerning the test are found in Appendix E. It was determined that the force required to trigger the landmines was 144 N in the center and 84 N on the side. Using an interaction area of 0.0027 m^2, these forces relate to pressures of 55.3 kPa and 31.1 kPa respectively. Tabulated score ranges are presented in Table 3.14. The tested values differ significantly from data obtained from the Canadian Force's Landmine Knowledge Database (2004), despite the side loads being comparable. Thus, it was assumed that values listed in the Canadian Force's database (Canadian Forces, 2004) are in fact the minimum required force values. An initial score corresponding to the center load of the PMN was used for a conservative evaluation, relating to a score of 1.

Table 3.14 Maximum interaction pressure scoring chart.

Interaction Pressure (kPa)	Score
150 and greater	5
120-150	4
90-120	3
60-90	2
30-60	1
0-30	0

3.4.2.1.2 Sensor Deflection

A tool capable of producing a larger relative sensor displacement increases the chance of landmine neutralization. An AP landmine requires both an applied load and a physical deflection for actuation of the trigger mechanism. A landmine will not detonate if the applied force does not result in the necessary deflection. There was little available data as to the specific deflections needed to trigger various landmines. Dr. V. Shankhla, Defense Scientist, Defense R&D Canada - Suffield, stated that "it is accepted that the deflections of AP mines can generally vary between 1.5 to 7.5 mm, for anti-vehicle mines the deflections are generally higher by about 50 to 100%". Independent tests performed on two PMN landmines in the Department of Agriculture and Bioresource Engineering, determined that that a 5.5 mm of vertical pressure plate displacement was needed to trigger the firing pin. Data relating to the PMN is found in Appendix E. A comparison of the force-displacement curves between the PMN's and sensors shows that a displacement of 5.5 mm on a PMN2 is comparable to a 2.3 mm deflection of the displacement sensor. It was not known whether a buried landmine would need this displacement, due to pre-compression from compacted/settled overlaying soil, or from undistributed loads or side loads, since no such data was available in current literature. Scoring was based on the 2.3 mm of displacement mentioned above which corresponds to a score of 1, as shown in Table 3.15.

Table 3.15 Sensor displacement scoring chart.

Displacement (mm)	Score
7.5+	5
6-7.5	4
4.5-6	3
3-4.5	2
1.5-3	1
0-1.5	0

3.4.2.1.3 Duty Cycle

The duration of an applied load affects the probability of landmine neutralization. A tool that applies a load for a longer period during the impact cycle is a better design. In many cases, a buried landmine will not actuate from a large magnitude, short duration impact, (as delivered by chain flails or other impacting devices) originating from the soil surface (GICHD, 2000). Due to internal and external dampening characteristics of a landmine’s mechanism, the response of a landmine will have a time constant, thus the duration of the applied load must be long enough to cause sufficient displacement needed to trigger the landmine. Many landmines, such as the PMN-2, T72 and others employ a dampening system in the form of an addition rubber pressure pad that covers the actual pressure sensing mechanism, often with a small air gap between the rubber and the pad. The rubber pad and air gap act as a damper for the landmine and may reduce dynamic loads interacting with the pressure plate by forming a reflective boundary since a large differences in material impedance exists (Dancygier and Yankelersky, 1996). In addition to dampening, there is evidence suggesting that the load duration can attenuate the interaction force of the landmine. Researchers have found that short loads applied over short durations cause a 'dynamic arching' effect which can attenuate the pressure sensed by the pressure pad (Chen *et al.,* 1996; Dancygier *et al.*, 1996; Dancygier *et al.,* 1999).

The average duration of a pressure pulse along with the average frequency will be used to calculate the duty cycle. The duty cycle represents the percentage of time a pulse is 'ON' during the impulse cycle and was determined by dividing the pulse time by the time between individual pulses. Larger duty cycles result in a higher score. Due to noise and interference in the initial test data, the pulse width was analyzed at a threshold of 100 N, which was approximately 10 kg of applied static mass. The 100 N mark was the tested approximate average static force needed to trigger a PMN landmine. The threshold reflects the static pressure needed to detonate common AP landmines. No data concerning the time dependent characteristics of common AP landmines was available. Therefore, the scoring table, presented in Table 3.16 is based on an assumed maximum value of 20%.

Table 3.16 Duty cycle evaluation chart.

Duty Cycle (%)	Score
20 and greater	5
15-20	4
10-15	3
5-10	2
0-5	1

3.4.2.1.4 Total Impulse

A device capable of delivering the highest possible impulse to a buried sensor has a greater ability of detonating a landmine. Research conducted by Stilling *et al.* (2003) measured the impulse imparted to load cells buried at a depth of 150 mm from human gait and from a rigid link flail devices. It was determined that for a human of 91 kg an impulse of 71 N-s was generated, while the flail generated a total impulse of 18.1 to 68.8 N-s. Based on the results, it was concluded that since similar impulse magnitudes were developed, the viability of impacting mechanisms would likely detonate AP landmines.

The total impulse delivered by an impacting mechanism was compared between mechanisms. The device capable of delivering the highest impulse is the better design. The total impulse scores used in the evaluation table were based on data obtained from Stilling *et al*. (2003), where the total impulse measured by a load cell buried at 150 mm from a 91 kg human gait (71 N-s) corresponds to a score of 1, as shown in Table 3.17.

Table 3.17 Total impulse evaluation chart.

Total Impulse (N-s)	Score
350 and greater	5
280-350	4
210-280	3
140-210	2
70-140	1
0-70	0

3.4.3 Results and Discussion

3.4.3.1 Results

The magnitudes of each evaluation parameter are summarized in Table 3.18. The weight of each parameter along with the score associated with each parameter magnitude is presented in 0. The paired comparison table used in calculating the parameter weight is shown in Appendix B, Table B.4.

Table 3.18 Summary of evaluation parameter magnitudes.

Parameter	Jackhammer Big Shoe			Jackhammer Small Shoe			Tamper		
	Pass			Pass			Pass		
	1	2	3	1	2	3	1	2	3
Maximum Interaction Pressure (kPa)	43	48	49	56.6	81.3	102.9	141	193	207
Total Impulse (N-s)	31.1	20.3	22.0	30.6	20.3	88.6	84.2	77.8	54.7
Total Displacement (mm)	0.67	0.93	0.71	0.99	1.48	2.56	1.89	2.67	1.34
Duty Cycle (%)	11.0	8.5	7.9	13.3	10.7	11.1	23.4	14.9	16.6

Table 3.19 Summary of evaluation parameter scores.

Parameter	Parameter Weight (%)	Jackhammer Big Shoe Score			Jackhammer Small Shoe Score			Tamper Score		
		Pass			Pass			Pass		
		1	2	3	1	2	3	1	2	3
Maximum interaction pressure	22.2	1	1	1	1	2	3	4	5	5
Total Impulse	11.1	0	0	0	0	0	1	1	1	0
Total Displacement	44.4	0	0	1	0	0	1	1	1	0
Duty Cycle	22.2	3	2	2	3	2	2	5	3	4

The results of the secondary design matrix are shown in Table 3.20. Total scores are presented per pass for each configuration. The design matrix is presented in Table B.5a, Table B.5b and Table B.5c of Appendix B.

Table 3.20 Secondary design matrix results.

Device	Pass 1 Score (%)	Pass 2 Score (%)	Pass 3 Score (%)	Average Score (%)
Tamper	48.15	43.70	40.00	43.95
Jackhammer Small Shoe	17.78	17.78	30.37	21.98
Jackhammer Big Shoe	17.78	13.33	13.33	14.81

Measurements such as soil compaction and changes in sensor depth were also made. These measurements are summarized below in Table 3.21.

Table 3.21 Summary of soil measurements.

Parameter	Jackhammer Big Shoe			Jackhammer Small Shoe 0.2 m			Tamper		
	Pass			Pass			Pass		
	1	2	3	1	2	3	1	2	3
Initial Soil Compaction (kPa)	0	182	315	0	218	505	0	496	860
Final Compaction (kPa)	182	315	341	218	505	639	496	860	945
Top Soil Displacement (mm)	43	11	02	61	15	40	78	17	60
Sensor Depth (mm)	204	161	159	210	149	134	256	178	161

Tests were also conducted with sensors buried at 0.10 m and 0.15 m in depths. Results for these tests are not shown since the thesis requirement was for a device to transmit sufficient forces up to 0.2 m. Note that the sensors used for the tamper were buried at a depth of 0.25 m, 0.05m deeper than the jackhammer tests.

3.4.3.1.2 Test observations

Soil effects: The first pass was associated with the lowest soil compaction and the highest sensor burial depth. After each pass, the soil was compacted further decreasing the sensor burial depth. The tamper resulted in the largest increase in compaction per pass, followed by the small shoe jackhammer configuration, then the big shoe configuration.

Operation: The tamper exhibited little difficulty in traversing the soil. The amplitude of its 'jump' was large enough to rise above the soil surface level for its next impact. During subsequent passes, it was noted that there was less resistance to forward motion. Both jackhammer configurations had difficulty traversing the soil. The jackhammer shoes slid across the soil surface and tended to dig into the loose soil. To alleviate this problem, a chain was attached to the bottom of the jackhammer and it was pulled (instead of pushed) along the soil. As the soil became more compact with subsequent passes, it was easier for the jackhammer to traverse the soil.

3.4.3.2 Discussion

During the first pass, the tamper system displayed significantly higher magnitudes in each evaluation parameter compared to the jackhammer configurations. This was reflected in the resulting score of 48.2% compared to 17.8% for each jackhammer configuration. The second pass resulted in the tamper scoring significantly higher than both jackhammer configurations. Both the tamper and big shoe jackhammer scores dropped 4.45% due to a drop in the duty cycle. The tamper again resulted in the highest score for the third pass, though the small shoe jackhammer score raised significantly from 17.8 to 30.4%. The increase in score was due to increases in the magnitude of each parameter.

From the design matrix results, as well as performance observations from the preliminary testing, the tamper was selected for further development and analysis. The results of the design matrix showed that the tamper consistently scored higher in each test pass, with the largest score difference between passes 1 and 2. The tamper system also displayed better operational characteristics with regards to mobility.

No testing standard was followed to compact the soil underneath the sensors placed in the trench. As such, the soil compaction as measured using the cone penetrometer, varied between 100 to 150 kPa. The forward travel speed used for the testing of each device was not precisely measured or controlled due to the devices being pushed manually across the soil surface, Thus, the effects of the forward travel speed on the evaluation parameters was not accounted for. The variation in soil compaction and forward travel speed may have an effect on the magnitude of the evaluation parameters, though due to the significantly larger parameter magnitudes for the tamper, the outcome of the design matrix and subsequent ranking of the mechanism was believed to be valid.

CHAPTER IV

FINAL DESIGN TESTING AND EVALUATION

The purpose of the final test phase was to further test and assess the demining effectiveness of the mechanism selected in the preliminary test phase, the tamper, and to determine optimal operational parameters. In conducting these tests, the following were achieved:

- a testing rig was designed, manufactured and fabricated for mounting the tamper to a prime mover. The prime mover for the tests was the carriage of the TMR so that the traversing velocity would be consistent. The design objective of the test rig was to create a low cost system for mounting the tamper for actual field usage;
- key evaluation parameters were identified for the assessment of the tamper performance and were used in conjunction with a design matrix. The evaluation parameters were based on those used in the preliminary testing phase (Section 3.4 *Preliminary Device Testing*), and included peak interaction pressure, sensor deflection, duty cycle and total impulse. An additional evaluation parameter, peak interaction pressure threshold, was added to the set of parameters; and
- two impact interface areas (shoes) were selected for determining an optimal tamper configuration. A large shoe with an interaction area of 0.092 m^2 and a smaller with an interaction area of 0.056 m^2 were used.

Observations from the preliminary test phase (Section 3.4 *Preliminary Device Testing*) indicated that the measured values taken from the load cells and deflection sensor were influenced by the procedure and testing conditions. For example, the compaction level of the soil and burial depth of sensors was noted to affect the magnitude of the measured data. As such, an evaluation using a consistent starting soil condition and sensor burial depth was important so measured values could provide valid evaluation data (as discussed in Section 4.2.1 *Evaluation Parameters*).

4.1 Apparatus and Procedure

4.1.1 Apparatus and Instrumentation

4.1.1.1 Tamper Mechanism

The tamper used for the final testing was a Wacker™ BS-60 (Wacker Construction Equipment AG, Munich, Germany) gasoline engine powered Tamper. The tamper physical and operational parameters are shown in Table 4.1. Two different sized tamper shoes were used during the testing, a 0.2 m x 0.28 m (Shoe 1-small) and 0.28 m x 0.33 m (Shoe 2-big).

Table 4.1 Tamper physical and operational parameter.

Specification	Tamper
Weight	62 kg
Power	2.3 kW
Impact frequency	11.7 bps
Compacting interface dimensions	Shoe 1: 0.2 m x0.28 m Shoe 2: 0.28 m x0.33 m

4.1.1.2 Test Rig

To achieve repeatable tamper operation between test runs, a rig was designed and fabricated to fasten the tamper to the TMR carriage. Note that a description of the TMR system is presented in Section 4.1.1.3 *Terra Mechanics Rig.* The rig was designed as a frame that can be easily modified for field testing and use on a prime mover. Figure 4.1 shows the tamper and test rig set up with the TMR carriage.

Figure 4.1 The tamper, test rig and TMR carriage apparatus.

The TMR carriage, essentially, pushed the test rig that held the tamper along the soil surface at a constant velocity. The rig contains a pivot point allowing tamper motion similar to the designed, human, hand-held operation mode. The test rig was designed to permit vertical tamper motion during impact without changing the impact angle and retained the ability of the tamper to rotate about the pivot point between the handle and tamper. The use of a vertical impact angle was chosen since the resulting force component from impact between the soil and tamper is maximized, allowing the subsequent pressure wave to propagate deeper into the soil. Since, the test rig was designed to be attached to a prime mover, such as a tractor or tank, for actual demining application, a modular design approach was adopted. As identified in Section 3.2.1 *Design Parameters,* a modular design is a positive design trait. An array of tamper and rig systems can be easily modified for different situations. A more detailed discussion of this concept regarding its use, limitations and recommendations for this design is presented in CHAPTER V. A schematic of the rig is shown in Figure 4.2. Refer to Appendix F for more detailed schematics.

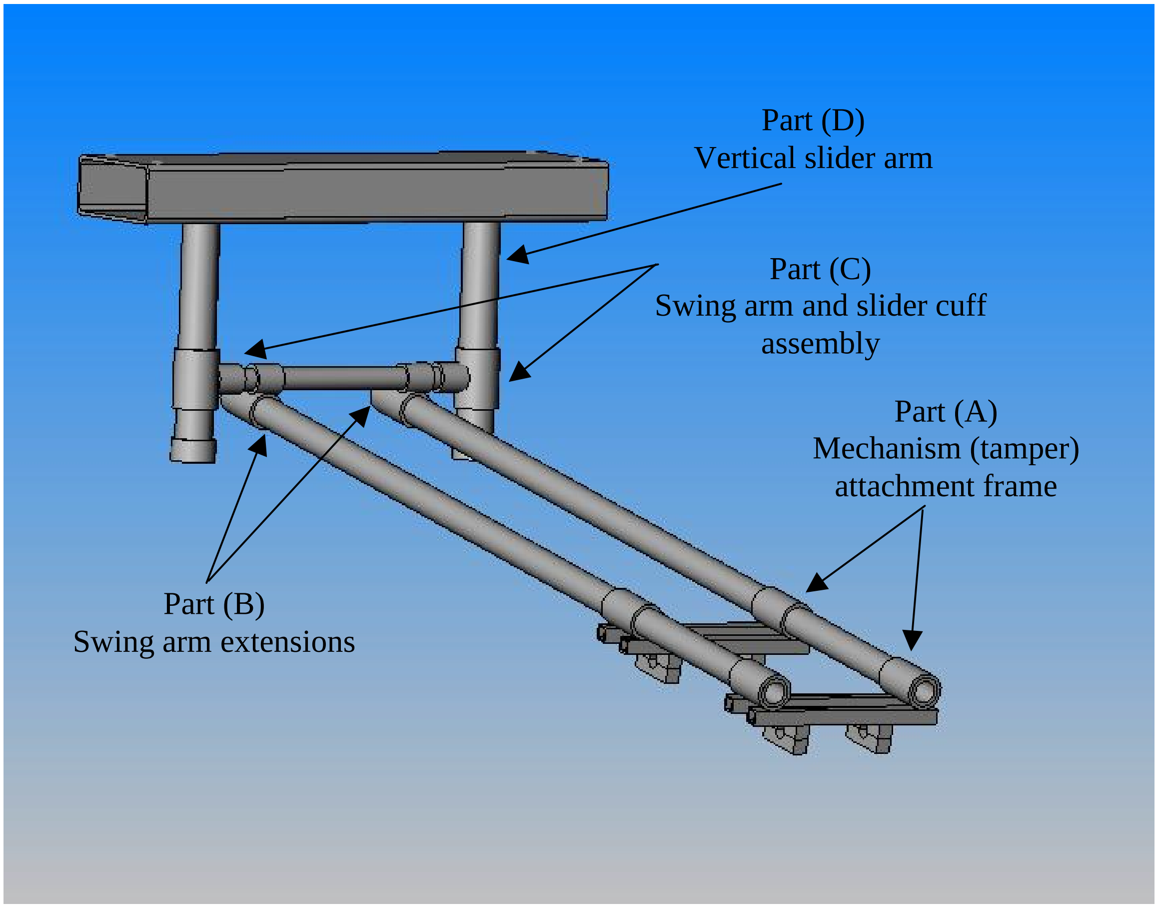

Figure 4.2 Schematic of the test rig.

The rig was composed of four main components; an adjustable holding frame connected to the tamper handles (Part (A) of Figure 4.2, two extension rods attaching the frame to a pivoting swing arm (Part (B) of Figure 4.2), a swing arm and slider cuffs assembly (Part (C) of Figure 4.2), and two vertical slider tubes attached to a mounting beam (Part (D) of Figure 4.2).

The tamper was attached to the rig system using an adjustable clamping system. The clamping system was composed of a two sets of 25.4 mm x 25.4 mm square tubing rods and four metal clamps welded to the bottom portion of each rod set, as seen in Figure 4.3. Cuffs were welded to the top sides of each rod, attaching the rods to the extension rods. The front cuffs were welded to the extension rods (Part (A.1) of Figure 4.3), while the position of the back two cuffs were adjustable (Part (A.2) of Figure 4.3). The frame was secured to the tamper by fastening the frame to the tamper handle using the clamps (Part (A.3) of Figure 4.3).

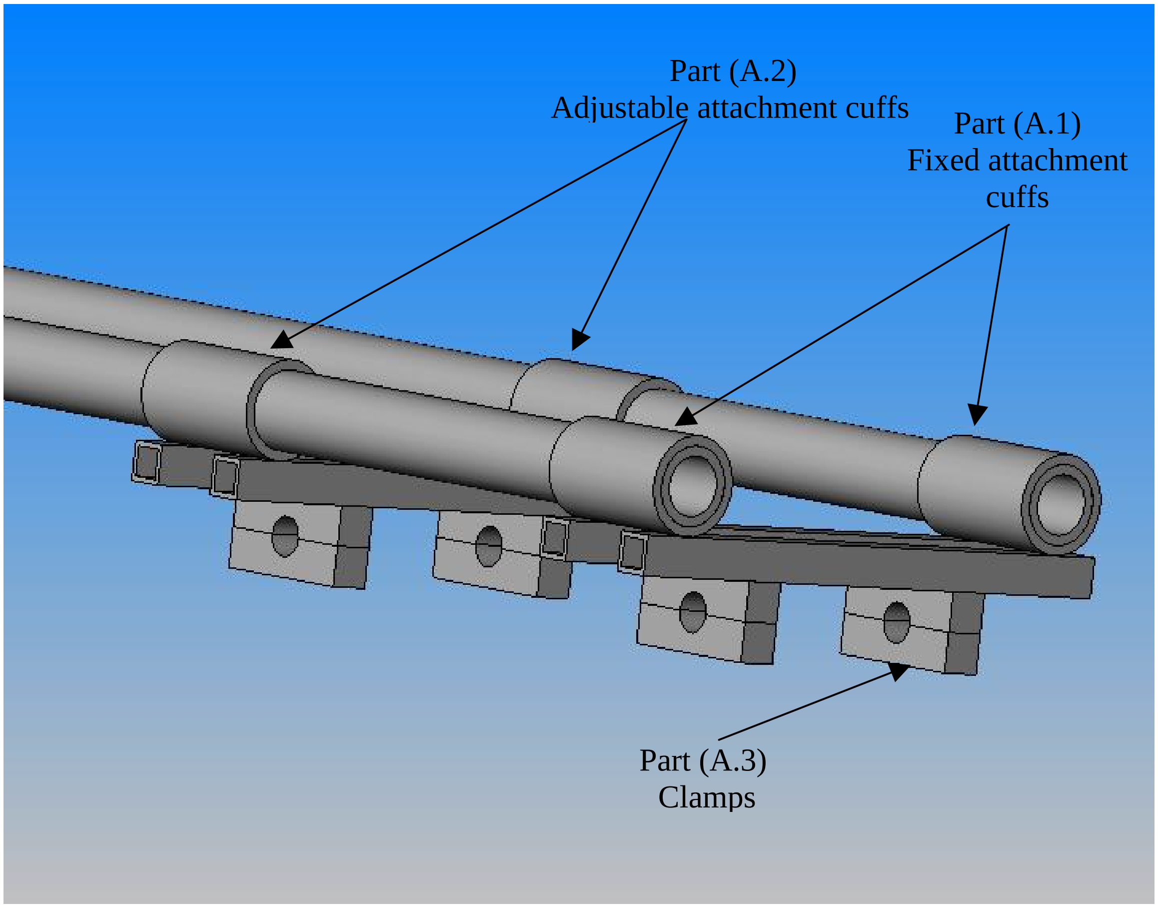

Figure 4.3 Part (A) – square holding frame and extension rods.

The extension rods extend past the tamper handles and fit attachment cuffs of the swing arm assembly, as detailed in Figure 4.4.

The swing arm assembly (Part (C.1) of Figure 4.4) was composed of two extension arm attachment cuffs, a rod fitting into vertical sliding cuffs at each end (Part (C.2) of Figure 4.4), and two vertical sliding posts (Part (C.3) of Figure 4.4).

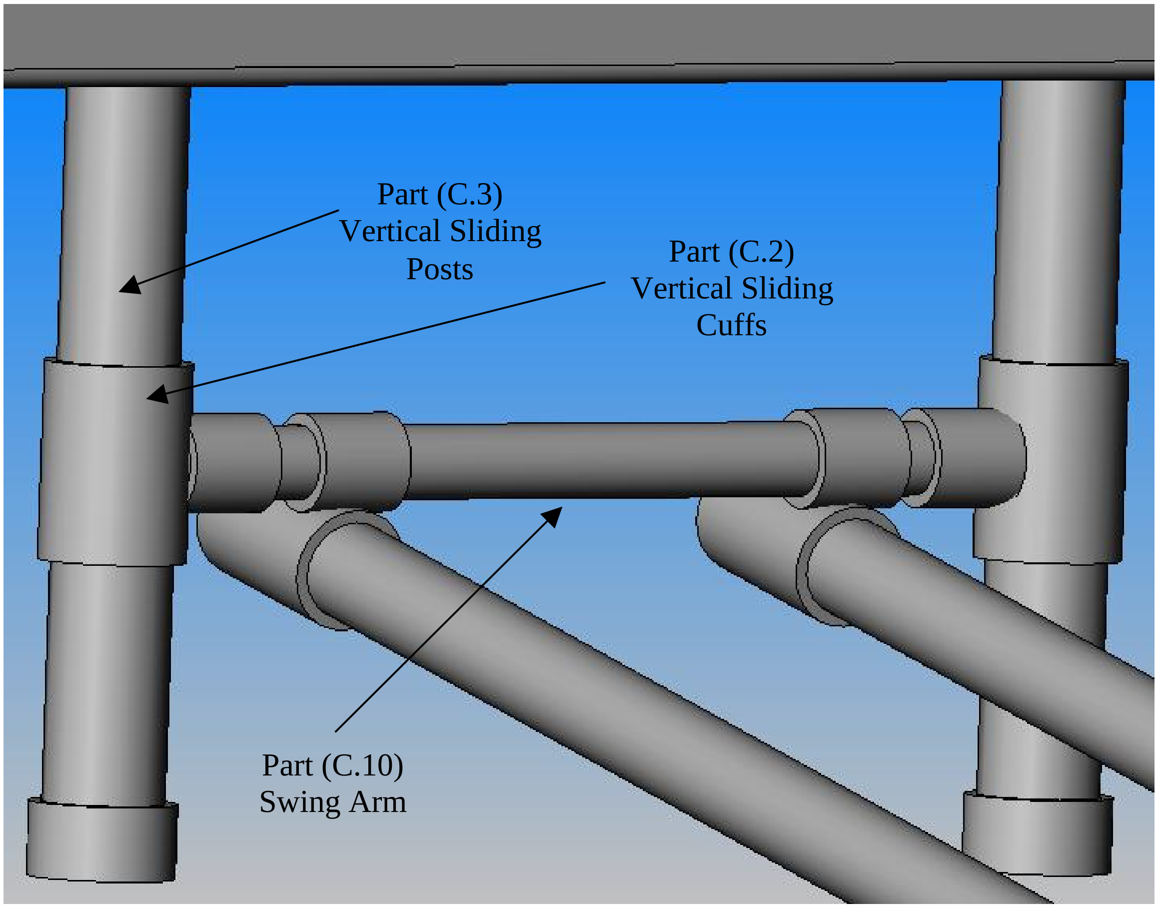

Figure 4.4 Part(C) Swing arm and slider cuff assembly

4.1.1.2.2 Test Rig Operation

To understand the operation of the tamper and test rig system, a brief description of the typical handheld operation of the tamper is given.

Handheld Tamper Operation: The motion of the tamper with a human operator is complex due to the multiple degrees of freedom associated with tamper motion. The tamper is not constrained to the vertical direction. As the tamper actuates, the operator holds the tamper handle, pushing forward and downwards, moving the tamper across the soil. Rubber dampers attaching the handles to the tamper body act as a pivot point, allowing the tamper to bound upward, maintaining a motion in a vertical plane, while the handle pivots around the operator's hand contact and also oscillate up and down with the motion of the tamper.

System Operation: At start-up, the tamper actuates upwards and downwards, in a slight arcing motion. The weight of the rig extension arms and swing arm assembly pushes downwards, while the extension arms push forward, initiating forward movement of the tamper. Rubber dampers attaching the handles to the tamper body act as a pivot point, allowing the tamper to bound upward, partially maintaining a motion in a vertical plane, while the system pivots around the swing arm and oscillates up and down via the slider cuffs. The slider posts are adjustable, allowing fine tuning of pivot distance. Collars at the base of the slider posts are adjustable – allowing the downward stroke of the tamper/swing arm system to be controlled.

4.1.1.3 Terra Mechanics Rig

The primary components of the TMR are a soil bin, carriage and soil processing tools. The soil bin is 0.76 m deep, 1.3 m long and 2 m wide. The carriage is hydraulically driven and is capable of supporting a variety of tillage tools and related instrumentation. The soil processing tools include a hydraulically driven rototiller, and rollers used for soil preparation.

4.1.1.4 Load Cells

Four Interface Technologies™ load cells based on a shear beam design were used for the final testing phase to measure the dynamic force transferred through the soil. The capacity and sensitivity of three of the load cells was 11.1 kN and 2.051 mV/V, respectively. The load cells were equipped with customized top and bottom interface to replicate the geometry of common AP landmines. Three load cells (referred to as LC 1 to 3) were equipped with a circular interface area of 4.42×10^{-3} m^2 and the base area was 8.63 $\times 10^{-3}$ m^2. The fourth load cell (referred to as LC 4) had a capacity and sensitivity of 2227 N and 2.156 mV/V respectively. The interface area of the fourth load cell was also 4.42×10^{-3} m^2, and had a square base area of 0.024×10^{-3} m^2. Past research conducted by Kushwaha *et al.* (2004), Sharifat *et al.* (2001) and Stilling *et al.* (2003) employed load cells with the larger square base area to aid in soil placement and sensor placement stability. Specifically, the base plate aided in creating a level surface that was perpendicular to the top soil. The load cell with a larger base area was included in these tests to determine the effects of the base area on the measured parameters.

4.1.1.5 Displacement Sensor

Refer to Section 3.4.1.1.5 Displacement Sensor for details.

4.1.1.6 Cone Penetrometer

Refer to Section 3.4.1.1.8 Cone Penetrometer for details.

4.1.1.7 Soil Type and Conditions

Refer to Section 3.4.1.1.2 Soil Parameters for details.

4.1.1.8 Signal Conditioner

Refer to Section 3.4.1.1.6 Signal Conditioner for details.

4.1.1.9 Data Acquisition System

Refer to Section 3.4.1.1.7 Data Acquisition for details.

4.1.2 Procedure

The typical usage of most mechanical demining systems employs multiple passes over a given area, usually 2 to 3 passes. Therefore, the tamper tests were conducted in sets of three passes over a given area. After each pass, the soil conditions vary greatly. Each consecutive pass resulted in a higher level of soil compaction. Initial soil compaction for the first pass was prepared to be low (approximately 100 kPa using the cone index) to maintain a consistent, initial soil compaction level and sensor burial depth. Note, realistically this may not represent many field conditions. However, hand-compacting the soil to a high level, as used in some mechanical demining tests, was judged to be too inconsistent, arbitrary and time consuming. Furthermore, using the TMR rollers to compact the soil after positioning the sensors changed the burial depth of the sensor from

200 mm in an uncontrolled manner, limiting the repeatability of the tests and introduced additional parameters to be measured.

The speed of the tamper was maintained at a constant speed, and was set by the limitations of the tamper (0.5 km/h for the small shoe and 0.44 km/h for the big shoe). The forward travel speed of the testing systems effects the interaction time between the impacting device and the buried sensors. Previous research on rollers, conducted by Booth, *et al.* (2004) indicated that the forward travel speed also affects the magnitude of the measured interaction pressure. Higher velocities increased the measured interaction pressure. Thus, a constant forward travel speed was deemed important.

The soil preparation procedure and sensor placement was completed as follows:

1. A soil sample was acquired prior to testing each morning to monitor and determine the moisture content of the soil.
2. Soil was rototilled two to three times, breaking up large clods to achieve a uniform soil texture. Soil was sprayed with water manually prior to rototilling as needed. The TMR leveling bar was used to level the soil surface. Two passes of a flat roller were used to compact the soil so that the surface level compaction was approximately 100 kPa and subsurface was approximately 200 kPa .
3. Wooden planks were placed in the middle of the bin as walking paths to minimize soil disturbances.
4. The test lane was prepared by digging six square holes, measuring approximately 0.25 m and 0.30 m depth. The holes were spaced 0.75 m apart and 0.75 m from the soil bin wall.
5. The bottom of each hole was leveled by hand and compacted by dropping a 0.1 x 0.1 m steel block from a height of approximately 0.5 m, to compact the soil between 200 kPa to 300 kPa.
6. Each load cell was calibrated by placing a 22.7 kg mass upon the pressure sensing interfacing area and adjusting the signal conditioner gains as necessary on a rigid foundation prior to placing in the test lane.

7. The force transducers and the displacement sensors were placed within the trench, so that the top surface of the sensor was 0.20 m below the soil surface. The position, type and depth of each sensor were recorded.
8. The holes were filled with the displaced soil in three layers. Each layer was compacted by dropping a 0.1 x 0.1 m steel block approximately 0.1 m above the ground, in an effort to compact the soil to the same level as the adjacent soil.
9. The initial soil surface height and soil compaction was measured adjacent to the load cell interface area.
10. Each load cell was zeroed using a voltmeter prior to each individual test.
11. The tests were performed using three passes of the tamper. There was no soil preparation between tests. The tamper was located approximately 1 m from the first sensor before starting. The TMR was started, and the carriage was accelerated to a forward travel speed of 0.5 km/h. As the tamper traversed the test path and the force transferred to depth and the sensor displacement were recorded. The top soil displacement, soil compaction and operational characteristics were also observed and recorded after each pass.
12. A second test series was performed on the other side of the soil bin, repeating steps 5 through 11.
13. After the two test series, the sensors were removed. The soil along and adjacent to the test path was manually tilled using shovels. Steps 2 through 4 were repeated, readying the soil for the next set of trials.
14. After a series of 5-6 tests, the subsoil had been compacted to a very high level. A steel shank used for tillage was employed to break up the subsoil.

4.2 Method of Analysis

The tamper shoe configurations were evaluated using the method as presented in Section 3.3 *Design Evaluation*, where evaluation parameters were developed and used in conjunction with a design matrix. An analysis of variance was performed to evaluate the effects of operational parameters.

4.2.1 Evaluation Parameters

The set of evaluation parameters, as outlined in Section, 3.3 *Design Evaluation*, included maximum interaction pressure, sensor deflection, duty cycle, total impulse and force threshold. The tamper configuration with the resulting highest score was judged to be the most suitable design. The two tamper configurations were evaluated per pass, as well as an average of the three passes. The mathematics and data analysis software Matlab® (The Mathworks Inc., Natick, MA) was used to calculate these evaluation parameters. The methods and algorithms used are presented in Appendix D.

4.2.1.1 Final Evaluation Parameters

The evaluation parameters used for the final test and evaluation were maximum interaction pressure, sensor deflection, duty cycle, total impulse and force threshold. In many cases, the evaluation scale was adjusted to reflect the parameter magnitudes. Additional parameters were included for a more thorough evaluation. These parameters were not included in the preliminary evaluation due to the limitations of the data sets, such as noise contamination, load cell sensitivity and poor control of the forward travel speed. The following section will highlight the changes in the evaluation scale and describe the new parameters.

4.2.1.1.1 Interaction Pressure

The scoring chart used in Section 3.4 *Preliminary Device Testing* had a top score of 5 points corresponding to interaction pressures above 150 kPa. The peak interaction pressures obtained from the final test were significantly larger than those obtained from the preliminary tests, thus the original scoring chart could not be used. The scoring chart was adjusted to compensate for the increase in interaction pressures, with the top score of 5 corresponding to pressures above 500 kPa, as shown in Table 4.2. Refer to Section 3.4.2.1.1 *Interaction Pressure* for details concerning the justification of the evaluation parameter.

Table 4.2 Maximum interaction pressures scoring chart.

Maximum Interaction Pressure (kPa)	Score
500 and above	5
400-500	4
300-400	3
200-300	2
100-200	1
0-100	0

4.2.1.1.2 Sensor Deflection

No changes were made to the scoring chart for the sensor deflection used in the preliminary tests. Refer to Section 3.4.2.1.2 *Sensor Deflection* for details concerning the validity of the evaluation parameter.

4.2.1.1.3 Duty Cycle

No changes were made to the scoring chart for the duty cycle evaluation chart. Refer to Section 3.4.2.1.3 *Duty Cycle* for details concerning the validity of the evaluation parameter.

4.2.1.1.4 Total Impulses

No changes were made to the scoring chart for the total impulse evaluation chart. Refer to Section 3.4.2.1.4 *Total Impulse* for details concerning the rational of the evaluation parameter

4.2.1.1.5 Maximum Impulse

The maximum impulse parameter was introduced as an additional evaluation parameter, but was not included in the design matrix evaluation. The maximum impulse was to be used in evaluating the possible response of a buried landmine to different magnitudes of impulses. The response of a landmine is affected by an impulse due to material properties such as flexibility and material stiffness. A stiff material may fracture or break when subjected to a high impulse, while a more flexible material will not be affected by such an impulse. Due to the numerous material and physical characteristics of AP landmines, it was not possible to construct a meaningful score chart for evaluations. As such, the maximum impulse was used in a discussion concerning the possible material and physical properties of different landmines, such as damping, or landmine material stiffness.

4.2.1.1.6 Interaction Pressure Threshold

A device capable of producing the largest number of interaction pressure peaks per pass increases the probability of landmine neutralization. As a demining device passes over a buried landmine, each impact produces a pressure wave that interacts with the landmine. If the interaction pressure is above the detonation threshold, the landmine may actuate and detonate. Multiple pressure peaks interacting with the landmine may increase the probability of detonation.

The scoring chart, shown in Table 4.3, was based on a median value of 63 hits and was calculated using the equation

$$hits = f_{impact} \times T_{interaction} \tag{4.1}$$

where f_{impact} is the impact frequency of the tamper as stated from the manufacturer to be 11.7 bps and $T_{interaction}$ was an assumed interaction time of 5.4 seconds. Interaction pressure peaks above 55.3 kPa (the interaction pressure needed to actuate a PMN), were used for scoring. As an additional threshold measure, the number of peaks above the interaction pressure 110.6 kPa (corresponding to two times the pressure needed to actuate a PMN) were also determined and scored using Table 4.3. The total score of both threshold levels was used in the evaluation table.

Table 4.3 Threshold scoring chart.

Number of Hits	Score
80 and above	5
70-80	4
60-70	3
50-60	2
40-50	1
Below 40	0

4.2.2 Statistical Analysis

To aid in the understanding of key parameters affecting the evaluation metrics, a statistical analysis of the measured parameters was performed to determine the effects of the operational parameters pass, load cell base area and tamper shoe size. The one way analysis of variance was performed per pass at a 5% level of significance. Test observations relating to the operational characteristics are presented.

4.3 Results and Discussion

4.3.1 Results

The average magnitudes (mean) and standard deviation (S.D.) and number of samples (N) of each evaluation parameter are summarized in Table 4.4 and Table 4.5. A summary of the measured soil parameters including initial soil compaction, final soil compaction and sensor burial depth is shown in Table 4.6 and Table 4.7. For more detailed information refer to Appendix G. Table G.1 and F2 presents the entire data set for each parameter.

Table 4.4 Summary of evaluation parameter magnitudes for the big shoe.

Parameter	Big Shoe								
	Pass 1			Pass 2			Pass 3		
	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
Peak Interaction Pressure (kPa)	274	304	15	344	56.1	23	389	66.7	18
Sensor Displacement (mm)	7.6	1.0	3	6.0	1.0	3	5.8	1.0	3
Duty Cycle (%)	9.5	1.2	12	8.8	0.6	16	8.3	0.98	16
Total Impulse (N s)	156	52.6	15	198	99.8	24	133	25.5	21
Max Impulse (N s)	4.5	1.3	15	5.1	1.0	22	5.1	0.8	21
Pressure Threshold (53.3 kPa)	70.7	6.90	11	67.5	11.38	14	74.4	15.0	16
Pressure Threshold (110.6 kPa)	59.3	16.5	14	56.6	4.27	16	55.3	7.95	18

S.D. = standard deviation
N = number of samples

Table 4.5 Summary of evaluation parameter magnitudes for the small shoe.

Parameter	Small Shoe								
	Pass 1			Pass 2			Pass 3		
	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
Peak Interaction Pressure (kPa)	304	45.8	30	367	71.8	33	378	88.8	27
Sensor Displacement (mm)	6.7	1.5	8	6.3	2.2	9	4.8	2.3	8
Duty Cycle (%)	10.2	1.0	23	9.5	2.8	24	7.8	3.4	26
Total Impulse (N s)	197	46.3	30	190	50.8	31	175	73.9	30
Max Impulse (N s)	5.1	0.7	30	6.1	1.4	34	6.1	1.5	33
Pressure Threshold (53.3 kPa)	74.7	7.44	18	71.5	12.6	21	73.2	14.2	21
Pressure Threshold (110.6 kPa)	68.2	11.6	22	59.8	9.58	25	56.3	4.77	24

S.D. = standard deviation
N = number of samples

Table 4.6 Measured soil properties for the big shoe.

Parameter	Big Shoe								
	Pass 1			Pass 2			Pass 3		
	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
Initial Soil Compaction (kPa)	496	112	29	2845	574	30	3916	660	30
Final Soil Compaction (kPa)	2845	574	30	3916	660	30	5062	1087	30
Sensor Depth (mm)	20.1	1.1	30	15.7	1.3	29	14.7	1.0	30

S.D. = standard deviation
N = number of samples

Table 4.7 Measured soil properties for the small shoe.

Parameter	Small Shoe								
	Pass 1			Pass 2			Pass 3		
	Mean	S.D.	N	Mean	S.D.	N	Mean	S.D.	N
Initial Soil Compaction (kPa)	483	146	42	3098	799	44	4189	1155	45
Final Soil Compaction (kPa)	3098	799	44	4189	1155	44	4824	1288	45
Sensor Depth (mm)	19.8	1.2	44	15.8	1.1	45	14.6	1.3	45

S.D. = standard deviation
N = number of samples

The resulting parameter score for each parameter, per pass, is shown in Table 4.8. The parameter weighting used in the design matrix are shown in the second column, is also included in Table 4.5. The final results of the design matrix are presented in Table 4.9. The paired comparison and design matrix tables used for the evaluation are shown in Table B.6, Table B.7a, Table B.7b, and Table B.7c in Appendix B.

Table 4.8 Evaluation parameter weighting and score.

Parameter	Parameter Weight (%)	Big Shoe Score			Small Shoe Score		
		Pass			Pass		
		1	2	3	1	2	3
Peak Interaction Pressure (kPa)	23.8	2	3	3	3	3	3
Sensor Displacement (mm)	28.6	5	4	3	4	4	3
Duty Cycle (%)	6.5	2	2	2	3	2	2
Total Impulse (N s)	4.8	2	2	2	2	2	1
Pressure Threshold (53.3 kPa)	14.3	4	3	4	4	3	4
Pressure Threshold (110.6 kPa)	19.1	2	2	2	3	2	2

Table 4.9 Final results of the design matrix.

Device	Pass 1 Score (%)	Pass 2 Score (%)	Pass 3 Score (%)	Average Score (%)
Tamper Small Shoe	67.6	59.1	56.2	61.0
Tamper Big Shoe	62.9	59.1	55.2	59.1

4.3.1.2 Performance Observations

Observations on the performance of the tamper system and rig follow:

- The rig permitted the tamper to jump, without restricting the vertical or rotational movement of the tamper, while maintaining forward travel speed. It was observed that the system allowed the tamper to overcome obstacles in the test path.
- The rig allowed the tamper system to conform to undulations in soil height (ranging in height from 12 mm to approximately 75 mm) without changing the vertical impact angle or restricting its movement. The system also permitted the tamper to jump over or climb obstacles such as large clumps of compacted soil.
- Both tamper configurations were able to traverse the soil. Tests on the small shoe were conducted at 0.5 km/h. At greater speeds, the shoe tended to dig into the soil. The big shoe had difficulty traversing the soil at a speed of 0.5 km/h. During operation at this speed, the shoe dug into the soil, restricting the forward movement of the system. Decreasing the forward travel speed for the big shoe to between 0.41-0.44 km/h alleviated the problem.
- The length of the extension arms was adjusted to full extension. From trial and error, it was determined that a larger pivot radius performed well, as the arcing radius decreased.

4.3.1.3 Design Matrix Evaluation

The general results of the design matrix evaluation for the two tamper shoe sizes are presented. A discussion relating to the design matrix follows in Section 4.3.2.2 *Design Matrix*.

During the first pass, the small shoe produced the highest score of 67.6% compared to 62.9% for the big shoe. The scores for the small and big shoe were equal for Pass 2. For the third pass, the small tamper shoe scored the highest at 56.2%, compared to 55.2% for the big shoe. The average score over all three passes was 61.1% for the small shoe and 59.1% for the big shoe.

4.3.1.4 Analysis of Evaluation Parameters

The results of an analysis of variance (ANOVA) of the evaluation parameters are presented in this section. Details of the statistical analysis are presented in Appendix H.

4.3.1.4.1 Peak Interaction Pressures

An analysis on the effect of load cell base area indicated that the difference between peak interaction pressure means between the two load cell base areas was not significant. Higher mean peak interaction pressures were observed for the small shoe during each pass, though the difference was not statistically significant. The peak interaction pressures for both shoe sizes increased per pass. The difference in means for both the small and large tamper shoes was statistically significant between the first and second pass and the first and third pass. The difference in means between passes 2 and 3 was not significant.

4.3.1.4.2 Sensor Displacement

The big shoe configuration produced larger mean displacements of the sensor during each pass, although the difference was not statistically significant. The sensor displacement means decreased per pass for both shoe sizes, with the largest drop between pass 1 and pass 2. The difference per pass was not significant for either shoe size.

4.3.1.4.3 Duty Cycle

There was a significant difference (P=0.05) between the mean duty cycle values of load cell base areas, where the load cell with the larger base area (LC 4) produced a larger mean duty cycle. This difference was significant during the first pass using the small shoe, and for the second and third pass with the large shoe. A higher mean duty cycle was observed for the small shoe, although there was no significant difference in duty cycle means between the two shoe sizes for each pass. The mean duty cycle decreased per pass with a significant difference between the first and third pass.

4.3.1.4.4 Total impulse

The mean total impulse for load cell with the largest base area (LC 4) was larger for the first and third pass using the small shoe and for the second pass using the big shoe. In all cases, there was not a significant difference in load cell means. The small shoe displayed a higher mean total impulse than the big shoe. There was a significant difference in the means between shoe sizes for the first and third passes. The difference in means between the two shoe sizes was not significant for the second pass. The mean total impulse decreased per pass for the small shoe, although the difference was not significant. For the big shoe, the second pass resulted in the highest total impulse. There was a significant difference in the mean total impulse for the big shoe between the second and third passes.

4.3.1.4.5 Interaction Pressure Threshold

The load cell with the largest area (LC 4) experienced a period of constant loading at a magnitude close to 55.3 kPa. Due to the calculation method used in the Matlab® (The Mathworks Inc., Natick, MA) script, threshold data for load cell 4 was not obtained and was not used for the first threshold level.

The number of peak interaction pressures above the 53.3 kPa and 110.6 kPa threshold levels was highest for the small shoe during each pass with the exception of third pass, where the big shoe had a higher mean. The difference during each pass was not statistically significant. At the 53.3 kPa threshold level, the number of peak interaction pressures decreased between Pass 1 and Pass 2, and increased between Pass 2 and 3 for both shoe sizes. The difference in means between passes was not significant for both shoe sizes. At the 110.6 kPa threshold level, the number of peak interaction pressures decreased per pass for both shoe sizes. The difference in means was significant for the small shoe, between Pass 1 and Pass 2. The difference in threshold means between the small and big shoe was not significant during each pass.

4.3.1.4.6 Maximum Impulse

It was not known directly how the magnitude of an individual impulse spike affects the displacement or detonation of a landmine, thus the maximum impulse was not used as an evaluation parameter. Data concerning the maximum impulse was collected, as it could affect the detonation or fragmentation of a given landmine due to material properties. A discussion of the maximum impulse is presented in Section 4.3.2.1.6 *Maximum Impulse*.

The mean values for the load cell with the larger base area (LC 4), using the big shoe, were higher during pass one and three, although the difference was not statistically significant. There was no significant difference in the mean maximum impulse values between the two load cell base areas. The maximum impulse was highest for the small tamper shoe during each pass and the difference was significant. The increase in maximum impulse was significant between the first and second passes. The difference between the second and third passes was not significant. In all three passes, there was a significant difference in means per tamper shoe size, with the small shoe delivering a larger mean.

4.3.2 Discussion

4.3.2.1 Evaluation Parameters

A discussion concerning the interpretation of physical meaning the evaluation parameters and their suitability in the design matrix is given.

4.3.2.1.1 Peak Pressure

The contact area between the soil surface and the tamper shoe affects the magnitude of the pressure wave transmitted to the soil and can be explained by the relation of pressure equals force divided by area. For a given force, a smaller area results in a larger magnitude pressure. The increased interaction pressure per pass was related to an increase in soil compaction levels and a decrease in the sensor depth as shown in Figure 4.5.

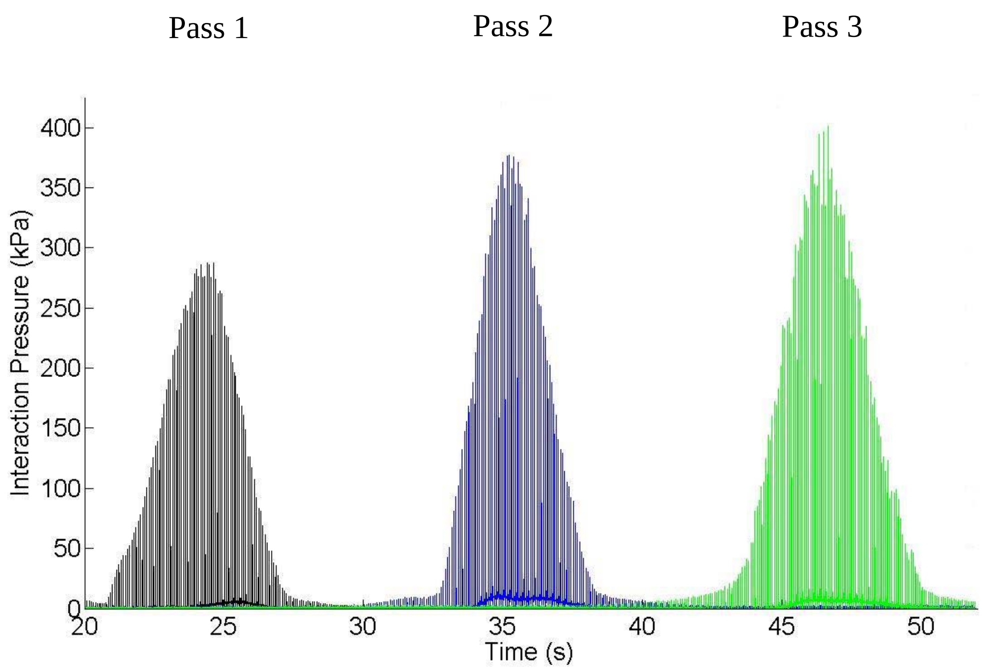

Figure 4.5 Typical interaction pressure profile per pass.

The interaction pressure profiles shown in Figure 4.5 correspond to Pass 1 (black), Pass 2 (blue) and Pass 3 (green). The Boussinesq equation predicts a higher interaction pressure due to a decrease in the concentration factor from 6 (wet/loose soil) to 4 (hard soil). A decrease in depth increases the load sensed by the buried landmine. As the polar position coordinate decreases in equation 2.10, the stress increases. As noted in Section 2.3 *Research and Theoretical Aspects Relating To Mechanical Landmine Neutralization*, both phenomena have been observed by previous research conducted by Kushwaha *et al.* (2004), Sharifat *et al.* (2001) and Stilling *et al.* (2003).

Accurately relating the interaction pressure magnitudes as measured by the load cells to magnitudes experienced by buried landmines was difficult due to differences in geometry, weight, material properties or dynamic characteristics. Differences in the measured interaction pressure were observed between the two load cell base areas, and those measured by the displacement sensor.

Load cells with two different base areas were used for the present test series to determine the effect of the base area on the measured values. The square plate was used in past research (Kushwaha *et al.*, 2004, Sharifat *et al.*, 2001, Stilling *et al.*, 2003) to aid in placing the load cells in the soil. It was later speculated that the additional base area may alter the magnitude of the measured interaction pressures. Other evaluation parameters, such as the duty cycle, maximum and total impulses and interaction pressure threshold values were all calculated from the interaction pressure. It was important to determine the effect of the base area on these parameters. The mean values of the evaluation parameters indicate that the larger base area does affect the measured and calculated values such as the interaction pressure, duty cycle, total and maximum impulse and interaction pressure threshold. As shown by the results of a one way ANOVA described in Section *4.3.1.4 Analysis of Evaluation Parameters*, the difference was only statistically significant for the duty cycle and interaction pressure threshold at the 53.3 kPa.

A possible reason for the different values may be due to the bearing capacity of the soil underneath the base plate. By increasing the base area, the bearing capacity of the soil underneath the sensor increases. Upon interaction with an incident pressure wave, the load cell would not deflect downward. In effect, the system was more 'stiff'. Thus, the measured interaction pressure and the values calculated from this parameter would be increased.

The interaction pressures measured by the load cells were significantly higher than those measured by the displacement sensors. Using the spring constant and the interaction area of the displacement sensor, the peak mean interaction pressure was calculated to be 167 kPa (corresponding to the third pass using the big shoe), significantly lower than the minimum peak interaction pressures seen by the load cells.

The reason for this difference may be attributed to many factors such as stiffness, deflection, weight as well as sensor limitations. The mass of the load cells was significantly larger than that of the displacement sensor, affecting measured values due to differences in inertial forces (Weiler and Kulhawy, 1982). The interface area of the load cells was composed of hardened steel and deflects a miniscule amount during interaction with an incident pressure wave. The displacement sensor on the other hand was composed of plastic and deflects significantly more than the load cell surface. The difference in measured values may be related to dynamic arching, as noted by Chen and Chen (1996) where stiffer materials experience higher loads, or due to the difference in sensor stiffness as compared to the surrounding soil. Stiffer sensors over-register the interaction pressure, while softer sensor under-register magnitudes (Weiler and Kulhawy, 1982). The deflection of the displacement sensor was limited to approximately 8 mm, due to physical design factors. Thus, the measured force may have been higher, though the interaction pressure profile of the displacement sensor indicates that the individual interaction pressure peaks leading up to the maximum interaction pressure peak were also significantly lower than the profile shown by the load cells.

4.3.2.1.2 Displacement

The displacement of the sensor was dynamic in nature and was a function of interaction pressure and time, due to the internal dampening of the sensor springs, the sliding friction between the two mating surfaces and the soil properties such as shear strength. The dynamic effects of the interaction between the incident pressure wave and sensor were apparent when looking at the displacement profile of the sensor, as seen in Figure 4.6.

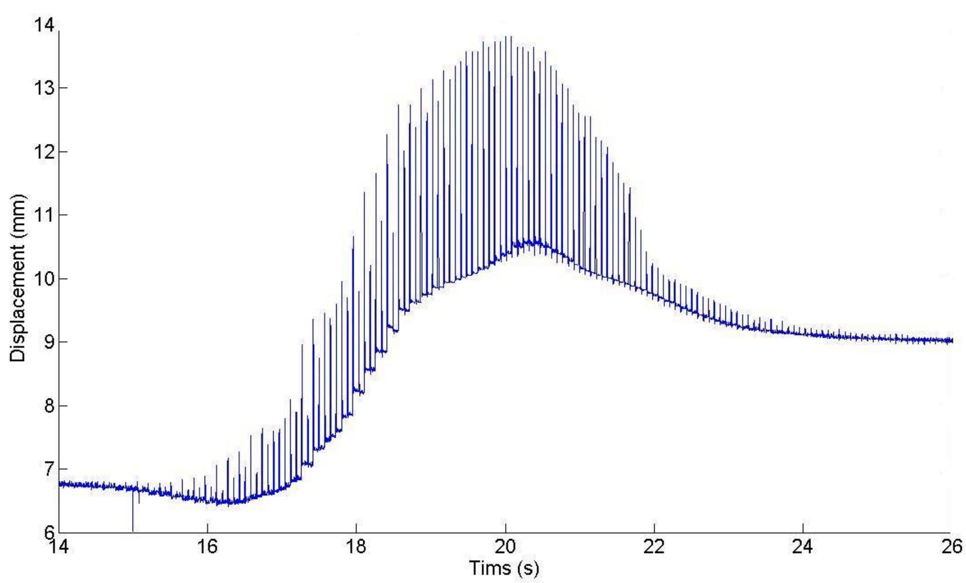

Figure 4.6 Displacement Profile of the displacement sensor.

Before each run, the sensor displayed an initial displacement. As the tamper approaches, incident pressure waves cause the sensor and overlaying soil to deflect downward, producing small individual spikes. The shear strength of the soil has not yet increased sufficiently to apply the required force needed to maintain the sensor compression. As the incident pressure waves become more intense (corresponding to impacts directly above or close to the sensor), the magnitude of the individual spikes increase, the magnitude of sensor deflection increases and the time period needed for the sensor to decompress increases. Due to the internal damping of the sensor and the increased shear strength of the soil from compaction, the sensor cannot return to its original position. As seen in Figure 4.7, with every impact, the local deflection minimum increases and the individual spikes increase. The interaction pressure profiles shown in Figure 4.7 correspond to Pass 1 (black), Pass 2 (blue) and Pass 3 (green).

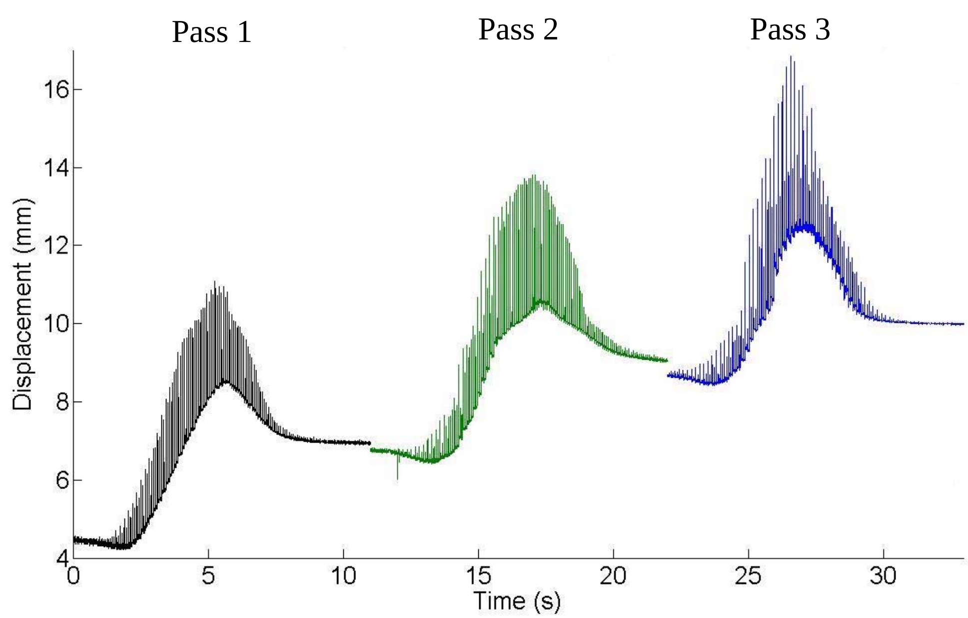

Figure 4.7 Typical displacement profile of the displacement sensor per pass.

During testing, the displacement sensor deflection was limited to approximately 8 mm. At this deflection, the sensors tended to bind. Thus, the actual displacement of the sensor may have been higher. The Canadian Center for Mine Action Technologies utilizes a similar sensor called a ‘Wirelessly Operated Reproduced Mine’ (WORMs) for testing of mechanical demining devices. From a correspondence with William Roberts (Military

Engineer, CCMAT/DRDC – Suffield), the sensors need approximately 2 mm of deflection, with a maximum static force of 150 N to actuate the MRM. Assuming the WORMs internal springs display a linear displacement, the spring constant was 75 kN/m. The spring constant of the displacement sensor was 46.3 kN/m. Thus a 2 mm displacement of the WORM corresponds to a 3.23 mm deflection of the displacement sensor. The sensors show that for each pass and shoe size; there was sufficient deflection to actuate these types of sensors.

Tests conducted of the load-deflection characteristics of a two PMN indicated that a displacement of 5.5mm of the pressure plate was needed to actuate the firing mechanism. As discussed in Section 3.4.2.1.2, a displacement of 5.5mm on a PMN2 is comparable to a 2.3mm deflection of the displacement sensor. The magnitude of displacement means shown in Table 4.4 are larger than the 2.3mm threshold for each pass and shoe configuration. The sensor deflection during the second and third pass decreased for both shoes as the actual force needed to compress the deflection sensors increased. Thus, for every sequential pass, a larger force was needed to compress the sensor which is consistent with linear spring theory. It was important to note that the burial depth of the displacement sensors decreased per pass from the initial burial depth of 200 mm, as seen in Table 4.5.

4.3.2.1.3 Duty Cycle

There was not a large variation between duty cycle magnitudes between passes for the small and big shoe. Data from the initial test phase indicated that the duty cycle from the first tamper model was larger than that of the tamper used in the final test phase, indicating the duty cycle may be heavily dependent on the particular machine. The statistical analysis did not show a significant difference between the means of the two shoe sizes. The magnitude of duty cycle values for the tamper used in the preliminary testing was significantly larger (with values of 23.4%, 14.9% and 16.6% for Pass 1, Pass 2 and Pass 3, respectively), suggesting that the duty cycle was heavily dependent on the actual machine itself. In both the preliminary and final test phases, the magnitude of the duty cycle decreased per pass, with a significant difference between Pass 1 and both Pass 2 and 3.

As presented in Section 3.4.2 *Method of Analysis*, depending on the dampening characteristics of the pressure sensing interface area, a larger duty cycle increases the potential of mine detonation. As seen in Table 4.4, except for the third pass, the duty cycle produced by the big tamper shoe was smaller than that of the small shoe configuration, yet the displacement sensor means are higher in each pass, contradicting the original assertion that a higher duty cycle results in more deflection. The dynamic characteristics of the sensor are not defined and may vary between tests due to wear and tear of the sensor, though this was not experimentally verified.

4.3.2.1.4 Total Impulse

The mean total impulse for the small shoe decreased per pass. The big shoe did not display this trend, as the total impulse for the second pass was a maximum, though this may be an anomaly. The calculated magnitudes of the total impulse can be compared to tests performed by Stilling *et al.* (2003) who, as previously described in Section 3.4.2.1.4 *Total Impulse*, found that the total impulse of a human for sensors buried in a similar soil at medium compaction at a depth of 150 mm was 71 N s. The total impulse for each pass and shoe configuration surpassed this amount, indicating that the feasibility of the tamper system was confirmed.

4.3.2.1.5 Interaction Pressure Threshold

The interaction pressure results for the 53.3 kPa threshold experienced a minimum for the second pass for both shoe sizes. This was a slight anomaly as the Boussinesq equation predicts that as soil compaction increases, the circles of iso-intensity become more circular, penetrating less into the soil. Thus, pass 3 (associated with the highest level of compaction) should correspond to a minimum number of hits. At the 110.6 kPa level, both shoe sizes reflected the theoretical implications of the Boussinesq equation.

The small shoe produced a larger mean interaction pressure magnitude in each pass, with the exception of pass 3. The forward travel speed used for testing the big shoe configuration was decreased from 0.5 km/h to between 0.41-0.44 km/h. As discussed in the introduction, data from roller studies indicated that the forward travel speed of a device affects the measured interaction pressure of a buried landmine (Booth *et al.*, 2004). The momentum of the system was larger at higher forward travel speeds. The difference may be attributed to different forward travel speeds.

4.3.2.1.6 Maximum Impulse

The small tamper shoe configuration consistently produced the largest maximum impulse per pass. The magnitudes did not change between pass 2 and 3, indicating that as the compaction increased, the maximum impulse saturated.

It was hypothesized that the maximum impulse values may give an indication of the response of different types of landmines due to the different materials used in the casing and interface area. A highly rigid or stiff casing is more likely to fracture under high impulses due to a low ductility. Landmine casings composed of hard or stiff materials may fragment, while landmines composed of softer materials may be less sensitive to such an impulse.

The interface pad used for landmines range from plastics to soft rubber. A harder interface pad would experience less load relief from dynamic arching, resulting in higher interaction pressures. Also, the impedance of a stiff material would more closely match that of surrounding soil – especially for hard, compacted soil, resulting in less of the pressure wave being reflected away. A pressure pad composed of softer materials would experience the opposite effect. There would be a greater difference in impedances between the soil and pad, resulting in the reflecting of the incident pressure wave.

4.3.2.2 Design Matrix

The results of the design matrix indicated that the small tamper shoe configuration was the most suitable design due to higher scores per pass as well as the higher overall score.

The results also indicated that there was little overall difference in performance between the small and big tamper shoe configurations. The statistical analysis supports this assertion as in most cases there was no significant difference in the mean values of the evaluation parameters

The design matrix scores suggest that both tamper shoe configurations were best employed using two passes, while there were marginal benefits in employing a third pass of the tamper system. Both tamper shoe configurations scored highest during the first pass. This was primarily due to the large sensor deflection. The overall scores per pass dropped significantly for the second pass. The decrease in score for the small shoe was due to a decrease in duty cycle and at both levels of the interaction pressure threshold scores. The decrease in score for the big shoe was due to a decrease in sensor displacement and the 53.3 kPa level interaction pressure threshold scores. The difference between the second and third pass was marginal and was primarily due to a decrease in the sensor displacement scores. While an additional third pass may increase landmine neutralization probabilities, the additional costs associated with maintenance, fuel costs, and an increase in soil compaction outweigh the benefits. A discussion of the optimal tamper application in demining situations is presented in *CHAPTER V Conclusions and Recommendations.*

4.3.2.3 Performance of the Testing Rig

It was not known whether the test rig would be a suitable system for driving the tamper. The review of current demining literature indicated that a similar mechanism to hold the tamper had not been used for demining or construction. The test rig system outperformed the expectations of the fabrication team.

The rig design was simplistic in nature and required no special parts. All materials used were easily acquired from local metal shops and were of standard size. The total cost of materials was estimated at $110 for an individual unit.

The rig system allowed for interchangeability between different tampers and configurations. The rig system was able to adjust for tamper height changes and pivot radius with respect to the swing bar. Although the present system accommodated three tamper models during the ‘try-out’ phase, future prototypes would require a more flexible clamping system to accommodate the variability in size and handle dimensions of tampers or similar devices.

In demining devices such as chain flails, changes in soil height correspond to a change in the angle of impact. As seen in equation 2.7, the magnitude of the vertical impact force component is a function of the impact angle. As previously stated in Section 4.1.1.2, *Test Rig*, a design objective was to allow the tamper freedom of movement in the vertical direction during impact without changing the impact angle. Changes in terrain such as obstacles (large pieces of compacted soil, approximately 0.15m in height) or undulating ground (up to 0.1 to 0.15 m in height) did not hamper this objective. The vertical sliding posts and corresponding cuffs allowed the tamper to adjust its location with respect to the soil by sliding upward or downwards without affecting the vertical angle of impact. The vertical motion and impact of the tamper also allowed for application close to vertical obstructions such as large rocks, walls or trees.

During testing, it was determined that the full length of the extension arms provided the best results due to a decrease in the arc and a more vertical motion. The rig design allowed for adjustment of the extension arms for different tamper systems. A tamper with softer rubber dampers may not need such a length, due to less restriction in the pivoting motion.

The modular design allowed a user to choose the number of tampers in an array. The rig system can be used for a variety of prime mover sizes, since a given number of modules can be chosen to conform to restriction imposed by the prime mover size or attachment area. The modular design characteristic also allows for flexibility in clearance width. The number of modules can be chosen to suit a specific criteria associated with clearance width. The clearance width can be shortened or lengthened to conform to clearance widths imposed by road or path width. A more detailed discussion of the application of the tamper system and rig is presented in CHAPTER V *Conclusions and Recommendations.*

In the event of a landmine blast, the tamper would swing upwards and pivot about the extension arms. The inertia of the tamper can be used to absorb much of the blast energy. A dampening system such as an air cushion or a simple spring could be used for additional absorption of the blast energy. It is possible that the forward travel speed and corresponding moment of the impacting tamper may shift the direction of the pressure bulb in front of the tamper shoe. Thus, a landmine may detonate in front of the tamper. In such a case, sufficient protection in terms of metal plating may be needed to protect the front area of the tamper.

A design flaw with the current rig was that if the tamper shoe becomes obstructed (as observed when the big shoe started digging into the soil), the present rig did not have a mechanism to correct this. During the development of the mechanism, the design flaw was identified and discussed, but was left for further consideration. The discussion raised the possibility of employing a trip mechanism. The solutions could employ a spring for the event of the tamper shoe becoming caught by and obstruction by displaced soil or another obstacle. The mechanical trip mechanism would be capable of quickly raising the tamper system allowing the tamper to overcome the obstacle. The mechanism could be similar to the spring loaded system used in agricultural cultivators. The springs in such a system allow the cultivator shank to bend back and ride over any obstructions and the stored energy in the spring corrects the shank to its original position once the obstacle is gone.

4.3.3 Conclusions

The demining effectiveness of a tamper system was evaluated using two shoe sizes. A test rig was fabricated to attach the tamper system to the carriage of the TMR. A design matrix was used to evaluate the demining effectiveness of a tamper system and to determine the optimal shoe configuration. A set of design parameters were developed to evaluate the tamper configurations. A statistical analysis using a one way analysis of variance (ANOVA) of the evaluation parameters was performed to determine the effects of operational parameters.

A summary of the effectiveness of the evaluation parameters to quantify the performance of the tamper systems follows.

- The peak interaction pressure as measured by the load cells was a useful tool as it compared the magnitudes between the two shoe configurations. The results can be compared to other demining tests if the procedural methods and test setup were similar. Relating the magnitudes of the peak interaction forces measured by the load cells to interaction pressures experienced by actual AP landmines was difficult due to differences in geometric and physical characteristics. Difference in magnitudes was illustrated when comparing values between the load cells and deflection sensors peak interaction pressure magnitudes.
- The deflection sensor was a useful tool for measuring demining effectiveness. The geometry and spring constant of the sensor was similar to common AP landmines. The deflection of the sensor can be related to other landmines or similar demining sensors (such as the PMN and WORMs) using the spring constant. The similarity of the dynamic characteristics between the sensor and AP landmines was not known and may affect the displacement magnitudes.
- The use of duty cycle as an evaluation parameter was not a practical parameter in comparing between the tamper shoe sizes, since the difference in magnitudes was marginal, although duty cycle may be useful in comparing different machines and models. Also, as the dynamic characteristics of common AP landmines were not known, a relation between the duty cycle and AP landmine response was difficult, as demonstrated by larger duty cycle and smaller sensor deflection values for the small shoe configuration, as opposed to smaller duty cycle magnitudes and larger deflections for the big shoe configuration. Due to the limited information available on the dampening characteristics of common AP landmines, a definite conclusion cannot be made concerning the effectiveness of this parameter in estimating the demining effectiveness of a demining system.

- The total impulse delivered from demining devices was a functional evaluation parameter as it can be compared to the total impulse generated from human gait.
- When properly applied, the interaction pressure threshold was a valuable evaluation parameter as it was an indicator or the extent of interaction between demining devices and buried landmines. Past demining research has measured the interaction time between demining devices and/or human gait and buried landmines by measuring the 'stance time', where the amount of time a given device interacts with a buried load cell (or landmine) above a defined pressure is measured (Sharifat *et al*., 2001; Stilling *et al*., 2003). The threshold parameter can be used as replacement of the stance time, as both quantify the degree of interaction. Note that a suitable threshold limit must be chosen to obtain valid results.
- Similar to the duty cycle, the applicability of using the maximum impulse was questionable at this time due to a lack of knowledge concerning the material and dynamic characteristics of common AP landmines. No definite conclusions can be made as to the reaction of various AP landmines to different magnitudes of individual impulses.

The design matrix scores indicated that the small tamper shoe outperformed the big shoe configuration. The difference between the scores for the two shoe sizes was marginal. The mean values for the small tamper shoe configuration were higher for many of the evaluation parameters during each pass, with the exception of the sensor displacement. The difference in means between the shoe sizes was not statistically significant except for the total impulse. Thus, the statistical analysis supports the conclusions of the design matrix. It was concluded that the optimal shoe configuration should be selected according to the demining environment that the device would be used in. A discussion pertaining to factors affecting shoe selection is presented in CHAPTER V *Conclusions and Recommendations.*

The design matrix and statistical analysis also indicated that the tamper device was best applied in two passes. The design matrix scores showed that the effectiveness of the tamper system decreases per pass. While the difference in scores was significant between the first and second pass, there was a marginal decrease between the second and third pass. The statistical analysis supported the results of the matrix, as in most cases the difference in the evaluation parameter means was significant between the first and second pass, but not between the second and third pass.

The performance of the test rig surpassed expectations. The rig allowed the tamper system to traverse the soil while maintaining vertical impact. The system also allowed the tamper to adjust to terrain changes such as soil undulations and obstacles. The rig was not able to correct situations where the tamper becomes restricted or embedded in the soil, though solutions to this design flaw exist, such as a trip mechanism as previously described.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

In developing a mechanical means for AP landmine neutralization, a design method was initiated and comprised of a concept generation phase, development of evaluation parameters, an evaluation phase using a paired comparison design matrix and preliminary testing of potential designs was implemented. The preliminary design phase resulted in the selection of one design concept, a tamper, for further evaluation. A test rig used to attach the tamper system to the Terra Mechanics Rig carriage was designed and built. The test rig was designed to allow the system to be to be attached to a prime mover, such as a tractor or tank, as could be used in real demining applications. Final testing was conducted in the Terra Mechanics soil bin, using two tamper shoe sizes and focused on the optimal operational parameters.

Initially, a brainstorming session was employed that generated a range of possible designs. Design concepts such as a dropping mass and slider-crank mechanism were identified for further investigation and analysis. Due to equipment accessibility and production costs, it was concluded that commercial, off-the-shelf equipment was best suited for further evaluation and included two pile driver configurations, a jackhammer, tamper and a vibratory roller.

Current evaluation protocols and the cataloging of available landmine clearance machines were used to develop the basic evaluation parameters. The parameters were further extended based on the deficiencies of current demining mechanisms and an understanding of AP landmine dynamics and soil-tool interaction. A design matrix, employing the initial set of evaluation parameters, was used to asses the potential design concepts. Additional mechanical demining devices currently used were included in the evaluation as a comparison to existing and proven mine neutralization technology. The top four designs from the design matrix included the jackhammer, Aardvark MK4 chain flail system, vibratory roller and tamper design concepts were suitable for further analysis. The Aardvark MK4 chain flail placed second in the design matrix, indicating that although chain flail systems do suffer performance issues, chain flails do have many positive traits. Although the vibratory roller scored the highest, a mechanism suitable for testing in a lab environment was not found. Thus, it was concluded that the jackhammer and tamper systems were to be used for preliminary testing.

The goal of the preliminary device testing was to evaluate the effectiveness of the jackhammer and tamper devices for landmine neutralization before any equipment alteration and a more detailed analysis were to be completed. Two shoe sizes were employed for the jackhammer. A design matrix was employed to evaluate the performance of the two concepts. Evaluation parameters were based on the interaction pressure, sensor deflection, duty cycle and the total impulse. The results of the tests indicated that the performance of the tamper system was superior to that of the jackhammer system. The tamper system resulted in significantly larger magnitudes in each evaluation parameter, as reflected by the evaluation scores of the design matrix.

The final testing phase focused on further evaluating the demining effectiveness of the tamper and to determine optimal operational parameters between two shoe sizes and the number of pass applications. A test rig was designed and fabricated to attach the tamper system onto the TMR for test automation. Using a design matrix and the evaluation parameters, interaction pressure, sensor deflection, duty cycle, total impulse and interaction pressure threshold. The design matrix results revealed that the small tamper shoe configuration performed better than that of the large shoe, but only marginally so. The results of a one-way ANOVA statistical analysis indicated that there was little difference between in the mean values of the parameters, supporting the results of the design matrix. It was thus concluded that the optimal shoe configuration may be associated with the demining environment the device would be used in. The design matrix also showed that the optimal application was two passes, as the design matrix scores differed little between the second and third passes. The statistical analysis also showed that there was no significant difference in most of the evaluation parameter means between the second and third passes. The performance of the test rig was more than adequate. The rig was able to allow the tamper to adjust to changes in terrain and overcome obstacles while maintaining a vertical impact strike.

The evaluation parameters used in the final testing phase included interaction pressure between buried load cells and the pressure wave generated from the tamper, the relative displacement of a deflection sensor, the duty cycle, the total impulse and the interaction pressure threshold. These parameters were used to quantify the capability of the tamper configurations to effectively neutralize a buried AP landmine.

5.2 Specific Conclusions

The main thesis objective was to develop a mechanical device for the neutralization of AP landmines, capable of generating sufficient force and ground deflection for detonating typical AP landmines buried to depths of 200 mm. Secondary design criteria included design simplicity, high durability and low maintenance, flexible operation and low power consumption. The following conclusions can be drawn:

- The measured magnitudes of the interaction pressure and sensor deflection indicated that the use of typical industrial tamper systems, such as the Wacker® gasoline powered tamper, were capable of generating very high magnitudes of interaction pressure and sensor deflection. Although the measured interactions pressures do not accurately correspond to the pressures seen by buried landmines, the parameter magnitudes were five to seven times higher than the 53.5 kPa pressure threshold needed to detonate a PMN AP landmine and two to three times higher than an average pressure threshold of 100 kPa of common AP landmines. The relative displacement of the deflection sensor also correlates to sufficient displacements for landmine actuation when compared to PMN data, the WORMs sensor used for mechanical demining tests by CCMAT, as well as the typical known displacement magnitudes of 1 to 6 mm of typical AP landmines. The magnitude of the duty cycle parameter varied substantially between the different tamper models used in the preliminary and final tests, though there was a marginal difference in duty cycle magnitudes between the tamper shoe sizes. There is limited information available on the dampening characteristics of common AP landmines. Thus, a definite conclusion cannot be made concerning the effectiveness of the duty cycle in estimating the demining effectiveness of a demining system. A similar situation exists for using the maximum measured impulse. The magnitudes of the total impulse surpassed the magnitudes of human gait measurements, indicating the feasibility of the tamper system for AP landmine neutralization. Although the interaction pressure threshold values were a useful tool in evaluating and comparing between the two tamper shoe sizes, the magnitudes determined for the final testing phase cannot be compared to other devices, as no data was available or benchmark set.

- The large magnitudes of interaction pressure, deflection sensor displacement and total impulse indicate that the tamper system fulfills the primary thesis objective. Of high importance was that after the first pass, the actual burial depth of the load cells and deflection sensor decreased to approximately 150 mm, 50 mm below the target depth of 200 mm, due to soil compaction above the sensors. Due to the large magnitudes of the evaluation parameters, it was believed that the tamper system would produce sufficient interaction pressures and soil deflection to actuate common AP landmines.
- The tamper system was based on a commonly found, off-the-shelf commercial system used in industrial construction. Thus, the availability of the tamper and accessibility of replacement components is increased. The tamper design itself was based on a simple slider crank design, self-powered by a two stroke motor. It was deemed possible that the design can be easily reproduced, modified or redesigned. Tampers are generally used in industrial settings and are subjected to harsh working conditions and long operating hours, suggesting that the tamper was highly durable. The response of the tamper to a blast from an AP landmine was not known and further research into the area, specifically live tests, are needed. The simplicity of design, availability of replacement parts and design durability imply that the tamper fulfills the requirement of low maintenance. The test rig was fabricated from materials found both in-shop and from local metal

shops. The rig design was simplistic in nature and required no special manufacturing, aside from general welding and cutting. It was noted that limited conclusions on the maintenance requirements of the test rig can be made due to limited operational hours.

- The performance observations of the combined tamper and rig system indicated that the tamper was able to conform to terrain changes such as terrain undulations and had the ability to overcome obstacles, while maintaining an optimal impact strike angle. Tests were conducted in low to high soil compaction magnitudes, suggesting that the combined system would perform in various terrains. Conclusions based on the performance of the tamper in different moisture ranges cannot be made due to the limited variations in soil moisture content employed during the tests. Further testing using a larger soil moisture content range may be needed. The modular design aspect also lends flexibility in application for terrains such as roads, paths, urban areas and forests.

5.3 Contributions

The following contributions were made during the development of the thesis project:

- By developing an extensive design matrix, employing evaluation parameters based on current mechanical demining technology deficiencies and known research relating to AP landmine dynamics and soil-tool interaction, a method of objective evaluation of mechanisms for AP landmine neutralization has been established.
- The advancement and understanding of the interaction between impacting landmine neutralization devices and sensors used in demining research has been established for the soil-tool interaction of impacting devices has been established. Particularly, the limitations of using rigid load cells and deflection based sensors have been found.
- Objective measures and methods for the performance comparison of mechanical demining devices have been furthered. The concept of using duty cycle and maximum impulse for quantifying the dynamic interactions between different AP landmine configurations has been proposed, though knowledge limitations have

not yielded definitive conclusions. The use of the interaction pressure threshold as a new metric provides fresh information as to the extent of interaction between demining devices and buried landmines.

- The concept of employing commercially available mechanisms used in industrial settings for the development of mechanical demining systems has been validated. Furthermore, as presented in the succeeding section, a mechanical system employing this model has been conceptualized, with recommendations on the application and further research paths provided.

5.4 Recommendations for Tamper/Rig System Application in Demining Scenarios

For proper application of the tamper/rig system application, the following recommendations are presented:

- The marginal difference of the design matrix results between the two tamper shoe configurations, as presented in Section 4.3 *Results and Discussion* suggests that the selection of optimal shoe size depends on the suitability of the shoe for a given situation, rather than the shoe size itself. Issues such as environment, terrain and land use should be used to determine the optimal shoe configuration for a given demining situation.
- A smaller shoe configuration is better suited for terrain that is rocky, pitted with holes or for undulating ground. It is possible that the performance of a smaller shoe would be less restricted by rough terrain. A smaller shoe width decreases the probability of an individual shoe ‘catching’ on obstructions. The smaller shoe area decreases the probability of missing interaction with a buried landmine due to the contact area of the shoe bridging overtop of a landmine located in a hole, between soil ridges or obstructions such as rocks or organic matter. A smaller shoe area is more likely to penetrate into smaller holes or soil undulations, decreasing skip zones. For AP landmines mines with a smaller displacement needed for actuation, the small shoe would be suitable, as smaller shoe area produced higher magnitudes of interaction pressures and threshold values. It was postulated that the small shoe may be more effective in neutralizing hard case AP landmines or

landmines with little dampening mechanism due to the higher maximum impulse magnitudes generated by the small shoe.

- As seen in Section 4.3 *Results and Discussion*, Table 4.5, both tamper shoes compact the soil to a great extent. The magnitude of the soil compaction was related to the number of passes. During the first pass, the initial soil compaction was light (with values increasing to approximately 500 kPa). This soil condition is comparable to soil that has been subjected to ground preparation, in which it is loosened and broken up, or vegetation removed using a flail system. For land intended for agricultural use, where soil compaction influences crop yield, a larger shoe area is beneficial due to a lower magnitude of soil compaction. If the system was used for additional passes, the use of the small shoe may be more suitable as the small shoe produced a smaller soil compaction during the third pass.
- It is recommended that the primary use of the tamper system be for area reduction or for area verification purposes. Though the tamper system preformed well during testing, it is not expected that the system will be 100% effective in all situations.
- Test results indicated that the tamper performed well in loose and highly compacted, dry soil. It is not known how the system would perform in wet or muddy conditions, though it is foreseeable that the system would have difficulties traversing the soil in these conditions. As such, it is recommended that the tamper system be used for dry soil conditions, though further testing is necessary for verification.
- As briefly discussed in Section *4.1.1.2 Test Rig*, the test rig was designed to maintain a vertical impact angle between the tamper and soil to maximize the vertical impact force, allowing the subsequent pressure wave to propagate deeper into the soil. Changing the impact angle could result in changes to power and blast protection requirements. By tilting the top of the tamper forward, the bounding motion of the tamper could be used to assist in propelling the prime mover or support vehicle behind it. Thus the powered needed for forward travel could be minimized. A negative aspect of a tilted impact angle is an alteration of

the pressure field. The pressure bulb resulting from the impact may be directed behind the tamper. Thus an AP landmine may detonate behind the tamper, subjecting the prime mover and the back of the tamper to the blast cone. By directing the impact away from the prime mover or against the direction or travel, a landmine may detonate further in front of the tamper system. The effects of the landmine blast on the prime mover would be decreased, though the front of the tamper would need sufficient protection from the blast cone of a landmine. Also, the bounding action of the tamper would work against the forward travel speed and momentum of the system, increasing the power requirements of the prime mover.

- The width of the tamper shoe may be increased or decreased as needed. A larger shoe width increases the clearance width of each operating module. Thus, in an array of modules, specifically when used in an overlapping pattern, the number of modules is decreased, increasing the cost effectiveness of the system. An increase in width does raise the possibility of missed mines during demining operation due to bridging overtop holes, soil undulations or rocks. The resulting pressure pattern and interaction with buried landmines created from an impact of a wide surface was not investigated during this research.
- Due to the possibility of landmine detonation in front of the incoming tamper module, it is recommended that sufficient protection for the front of the tamper be included.
- The use of a modular design allows the tamper and rig system to be used in an array for demining situations. The use of an array allows for two application advantages: an overlapping application per pass, and a flexible array configuration for differing terrain and prime mover arrangements.
- An array of tampers permits for an overlapping application pattern in which during a single pass, a given section of soil is impacted twice. As discussed in Section 4.3.2.2, *Design Matrix*, it is supposed that two passes is the optimal number of passes. A larger shoe area or a larger width is best suited for an overlapping configuration because dimensional limitations posed by the holding

rig can be overcome, as well as reducing the number of tamper modules in an array.

- An array of tamper modules can be configured to fit the requirements set out by clearance path limitations or the dimensions of a prime mover in use. A smaller number of devices could be attached to a smaller prime mover to clear small pathways in forested or urban environments. A greater number of tamper modules can be fitted to a larger prime mover to clear a larger width. The modular tamper system also allows for each module to conform to changes in terrain (such as localized terrain undulations) without affecting the performance of adjacent modules.

5.5 Recommendations for Future Research

Based on this thesis project, the following future research is recommended:

- Time and lab resources limited the scope of testing to one soil type and a small range of soil moisture content. Further research on the performance of the tamper system in differing soil compositions and larger variations of soil moisture contents is needed. Additional test scenarios including the effects of overlying vegetation and other obstructions are needed to determine the limitations of the tamper/rig system in varying environments.
- The interaction between the pressure bulbs created from multiple tamper module impacts as seen in an array (side by side or overlapping pattern) needs investigation to enhance possible demining operations.
- A proper correlation between sensors used in demining research and actual AP landmines must be investigated. The dynamic characteristics of the sensors and their relation to actual AP landmines must be investigated. As such, the validity of using duty cycle and maximum impulse as evaluation metrics can be established. The relation between the physical aspects of the sensors such as geometry and weight needs additional consideration.
- Additional consideration as to the effects of an actual blast from AP landmines or surrogate charges on the tamper and rig system are needed. Specifically, a method

of absorbing the energy impacted on the system is recommended for further analysis.

- Optimization of the physical setup of the tamper-rig needs to be pursued for the best possible demining effectiveness and overall performance. The physical configuration of the system, such as the length of the extension rods, impact angle, and shoe profiles (width, length and/or surface interface design) are recommended for future research.

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Appendix A Unit Assignment Associated with Landmine Actuation and Impact Energy

The purpose of this appendix is to provide details for assigning units with respect to mass (kg) and force (N), pressure (kPa) and impact energy (J).

The majority of literature relating to landmine actuation (such as the Canadian Forces (2004)) quantifies the load needed to actuate a landmine in terms of the application of a static mass, m, reported in kilograms (kg). For the purposes of this thesis, references to static load have been converted into a static force in terms of Newtons (N) to achieve consistency in reporting throughout the thesis. The use of Newtons permits easy comparisons to be made with the experimental data as measurements have been reported in units of force since the measuring sensors (load cells and deflection sensors) were calibrated in terms of Newtons per voltage. Force, F, is determined by the equation:

$$Force = mass \times gravity \tag{A.1}$$

Due to the variation in the pressure interface areas of different AP landmine types, as well as the sensors used for testing purposes, measured data was converted into a pressure (kPa) to further aid in comparisons between AP and related instrumentation.

$$\Pr essure = \frac{Force}{Interface\_\ Area} \tag{A.2}$$

As described in section *Impact Force/Energy Comparison 3.2.1.1*, kinetic energy was used to compare the total possible energy produced by a device before impact, since determining the actual force imparted to the soil from different impacting devices is not feasible. As described in Sections *2.3.1 Energy Transfer and 2.3.2 Impact Force*, the resulting impact force is a complex function of operational parameters and soil characteristics. In most cases, it was not viable to obtain data relating to the different operational parameters and soil properties. Also, data obtained from different commercial impacting devices (such as the tampers, jackhammers and pile drivers) rate their respective devices in terms of impact energy. Thus, the unit of Joules was used for comparing the total possible energy of a device before impact.

Appendix B Design Matrix and Paired Comparison

This appendix presents the data used in the design matrices for Section 3.3.2 *Design Matrix Results*, Section 3.4.3.1 *Results, and* Section 4.3.1 *Results*.

Table B.1 contains the paired comparison data used to determine the parameter weights for the evaluation parameters used in Section *3.3 Design Evaluation*. As noted in Section *3.3 Design Evaluation*, It was not possible to quantify the costs associated with fabrication, acquisition or cost effectiveness of devices due to insufficient knowledge. Thus, the total cost of a design was evaluated on the resulting evaluation scores for the following parameters; power requirements, design performance, maintenance, durability, and fabrication and/or acquisition costs, as given in Table B.2.

Table B.1 Paired comparison matrix for preliminary evaluation parameters.

Criteria	Kinetic Energy	Impact Frequency	Power Requirements	Design Flexibility and Performance	Soil Effects	Design Simplicity and Maintenance	Durability and Strength	Cost	Total Score	Weighting Factor
Kinetic Energy	1	1	1	0	1	0	0	1	5	13.9
Impact Frequency	0	1	1	0	1	1	0	1	5	13.9
Power Requirements	0	0	1	0	1	0	0	1	3	8.3
Design Flexibility and Performance	1	1	1	1	1	1	0	1	7	19.4
Soil Effects	0	0	0	0	1	0	0	0	1	2.8
Design Simplicity and Maintenance	1	0	1	0	1	1	0	1	5	13.9
Durability and Strength	1	1	1	1	1	1	1	1	8	22.2
Cost	0	0	0	0	1	0	0	1	2	5.6
									36	100

Table B.2 contains the paired comparison matrix used to determine the weight of the 'cost' evaluation parameter used in Table B.1, as described in Section *3.2.1.8 Costs*.

Table B.2 Paired comparison matrix for the preliminary evaluation parameter 'Cost'.

Criteria	Power Requirements	Design Flexibility and Performance	Design Simplicity and Maintenance	Durability and Strength	Costs	Total Score	Weighting Factor
Power Requirements	1	0	0	0	1	2	13.3
Design Flexibility and Performance	1	1	1	0	1	4	26.6
Design Simplicity and Maintenance	1	0	1	0	1	3	20
Durability and Strength	1	1	1	1	1	5	33.3
Cost	0	0	0	0	1	1	6.6
						15	100

Table B.3 contains the actual design matrix used to evaluate the potential designs in Section 3.3.2 *Design Matrix Results*.

Table B.3 Design matrix for the preliminary evaluation.

Criteria	Total Possible Score	Diesel Pile Driver		Fence Post Driver		EXA18 Roller		MT-76d Rammer		Jack Hammer		Pearson Roller		Aardvark	
Kinetic Energy	5	4	11.1	5	13.9	0	0.0	0.5	1.4	1.5	4.2	0	0.0	3	8.3
Impact Frequency	4	0	0	0	0	4	13.9	2	6.9	3	10.4	2	6.9	3	10.4
Power Requirements	10	8	6.7	8	6.7	6	5.0	10	8.3	6	5.0	9	7.5	9	7.5
Design Flexibility and Performance	24	10	8.1	12.5	10.1	17	13.8	18	14.6	22	17.8	14.5	11.7	14	11.3
Soil Effects	6	3	1.4	4.5	2.1	4.5	2.1	3	1.4	3.5	1.6	2	0.9	3	1.4
Design Simplicity and Maintenance	18	10.5	8.1	11.5	8.9	10.5	8.1	12	9.3	16	12.3	15	11.6	12.5	9.6
Durability and Strength	12	7	13.0	5.5	10.2	10.5	19.4	7.5	13.9	10	18.5	6.5	12.0	8.5	15.7
Costs	n/a		2.9		2.9		3.8		3.8		4.3		3.5		3.6
Score			51.3		54.7		66.1		59.5		74.2		54.2		68.0

Table B.4 contains the paired comparison matrix used to determine the parameter weights for the evaluation of the tamper and jackhammer configurations in Section *3.4.3.4 Results*.

Table B.4 Paired comparison matrix used for the preliminary test evaluation parameters.

Criteria	Peak Pressure	Peak Displacement	Total Impulse	Duty Cycle	Total Score	Weighting Factor
Peak Pressure	1	0	1	0	2	22.2
Peak Displacement	1	1	1	1	4	44.4
Total Impulse	0	0	1	0	1	11.1
Duty Cycle	0	0	1	1	2	22.2
					9	100.0

Table B.5a, B.5b, and B.5c contain design matrices used for the evaluation of the tamper and jackhammer configurations per pass, as seen in Section 3.4.3.4 Results.

Table B.5a Design matrix used for the preliminary test, pass 1.

Criteria	Total Possible Score	Tamper		Jack Hammer (big)		Jack Hammer (Small)	
Peak Pressure	5	4	17.8	1	4.4	1	4.4
Peak Displacement	7.5	1	5.9	0	0.0	0	0.0
Total Impulse	5	1	2.2	0	0.0	0	0.0
Duty Cycle	5	5	22.2	3	13.3	3	13.3
Score			48.1		17.8		17.8

Table B.5b Design matrix used for the preliminary test, pass 2.

Criteria	Total Possible Score	Tamper		Jack Hammer (big)		Jack Hammer (Small)	
Peak Pressure	5	5	22.2	1	4.4	2	8.9
Peak Displacement	7.5	1	5.9	0	0.0	0	0.0
Total Impulse	5	1	2.2	0	0.0	0	0.0
Duty Cycle	5	3	13.3	2	8.9	2	8.9
Score			43.7		13.3		17.8

Table B.5c Design matrix used for the preliminary test, pass 3.

Criteria	Total Possible Score	Tamper		Jack Hammer (big)		Jack Hammer (Small)	
Peak Pressure	5	5	22.2	1	4.4	3	13.3
Peak Displacement	7.5	0	0.0	0	0.0	1	5.9
Total Impulse	5	0	0.0	0	0.0	1	2.2
Duty Cycle	5	4	17.8	2	8.9	2	8.9
Score			40.0		13.3		30.4

Table B.6 contains the paired comparison matrix used to determine the weights of the evaluation parameters for the final test evaluation parameters, as seen in section 4.3.1 *Results.*

Table B.6 Paired comparison matrix used for the final tests.

Criteria	Interaction Pressure	Sensor Deflection	Duty Cycle	Total Impulse	Interaction Pressure Force Threshold (1)	Interaction Pressure Force Threshold (2)	Total Score	Weighting Factor
Interaction Pressure	1	0	1	1	1	1	5	23.8
Sensor Deflection	1	1	1	1	1	1	6	28.6
Duty Cycle	0	0	1	1	0	0	2	9.5
Total Impulse	0	0	0	1	0	0	1	4.8
Interaction Pressure Force Threshold (1)	0	0	1	1	1	0	3	14.3
Interaction Pressure Force Threshold (2)	0	0	1	1	1	1	4	19.0
Score							21	100.0

Tables B.7a, Table B.7b and Table B.7c are the design matrices used for the final evaluation of the tamper configurations as seen in Section 4.3.1 *Results.*

Table B.7a Design matrix used for the final test, pass 1.

Criteria	Total Points Possible	Small Shoe		Big Shoe	
Interaction Pressure	5	3	14.3	2	9.5
Sensor Deflection	5	4	22.9	5	28.6
Duty Cycle	5	3	5.7	2	3.8
Total Impulse	5	2	1.9	2	1.9
Interaction Pressure Force Threshold (1)	5	4	11.4	4	11.4
Interaction Pressure Force Threshold (2)	5	3	11.4	2	7.6
Score			67.6		62.9

Table B.7b Design matrix used for the final test, pass 2.

Criteria	Total Points Possible	Small Shoe		Big Shoe	
Interaction Pressure	5	3	14.3	3	14.3
Sensor Deflection	5	4	22.9	4	22.9
Duty Cycle	5	2	3.8	2	3.8
Total Impulse	5	2	1.9	2	1.9
Interaction Pressure Force Threshold (1)	5	3	8.6	3	8.6
Interaction Pressure Force Threshold (2)	5	2	7.6	2	7.6
Score			59.0		59.0

Table B.7c Design matrix used for the final test, pass 3.

Criteria	Total Points Possible	Small Shoe		Big Shoe	
Interaction Pressure	5	3	14.3	3	14.3
Sensor Deflection	5	3	17.1	3	17.1
Duty Cycle	5	2	3.8	2	3.8
Total Impulse	5	2	1.9	1	1.0
Interaction Pressure Force Threshold (1)	5	4	11.4	4	11.4
Interaction Pressure Force Threshold (2)	5	2	7.6	2	7.6
Score			56.2		55.2

Appendix C Displacement Sensor Calibration

The displacement sensor was calibrated by determining the electrical output voltage (V_o) of the sensor with respect to displacement (x). An Instron Universal Testing Machine (Instron, Norwood, MA) was used to compress the sensor. The sensor output voltage and sensor deflection were manually measured. The equation relating V_o and the compression force (F) to the sensor displacement was determined by plotting the voltage vs. displacement, as shown in Figure C.1, and compression force vs. displacement, as shown in Figure C.2 in MS Excel. A trend line was added to each curve to determine the displacement and force equations. The displacement equation is given by Equation (C.1) while the force equation is given by equation (C.2). The raw data is presented in Table C.1.

$$x(mm) = 10.74V_o^6 - 139.1V_o^5 + 716.5V_o^4 - 100V_o^3 + 279V_o^2 - 2065.8V_o + 642.28 \qquad \text{(C.1)}$$

$$F(N) = 46.4x + 33.047 \qquad \text{(C.2)}$$

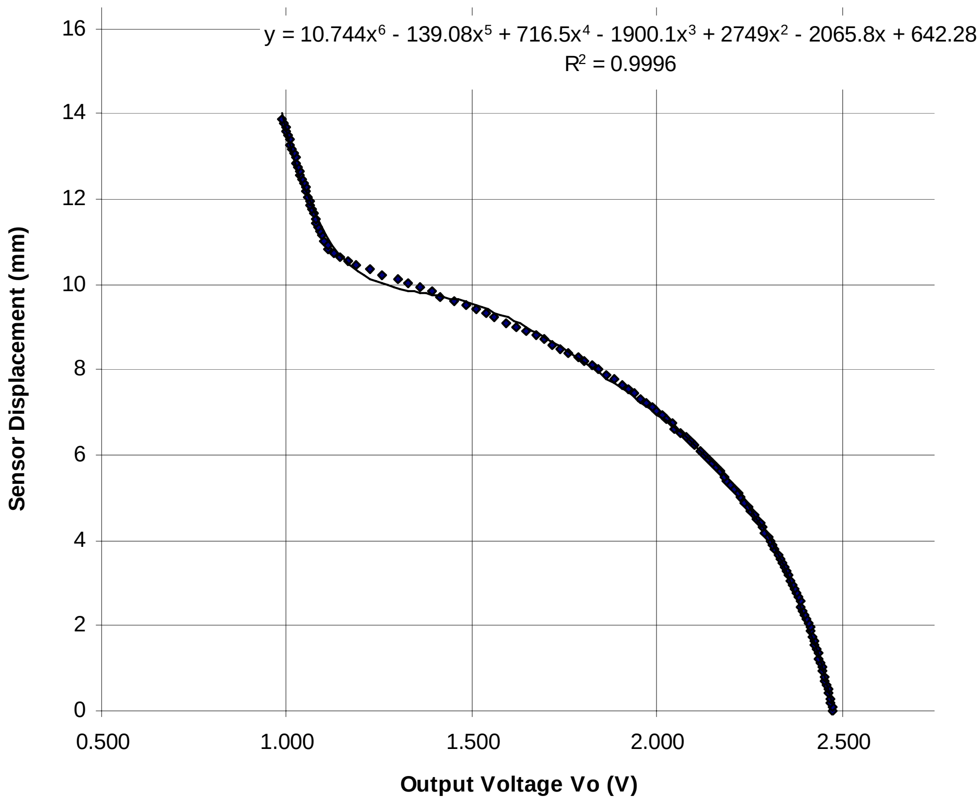


Figure C.1 Sensor calibration curve.

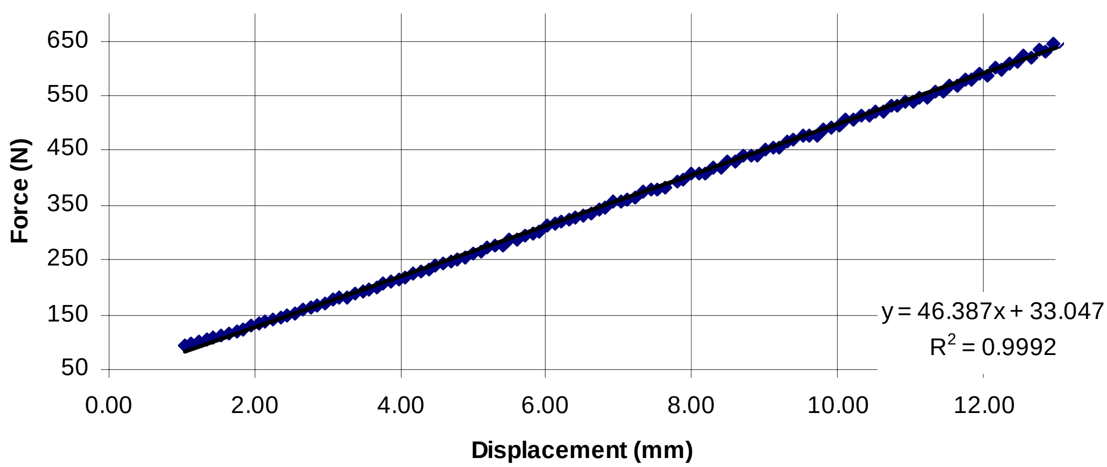


Figure C.2 Sensor force displacement curve.

Table C.1 Raw data for displacement sensor calibration.

V_0 (V)	F (N)	x (mm)	V_0 (V)	F (N)	x (mm)	V_0 (V)	F (N)	x (mm)
2.474	20.00	0.000	2.263	247.50	4.591	1.562	467.50	9.212
2.473	36.25	0.100	2.254	252.50	4.691	1.540	468.70	9.312
2.470	57.50	0.200	2.245	256.20	4.791	1.510	477.50	9.412
2.467	58.75	0.300	2.236	262.50	4.891	1.484	478.70	9.525
2.464	72.50	0.400	2.227	266.20	5.004	1.453	478.70	9.625
2.462	76.25	0.500	2.218	271.20	5.104	1.415	490.00	9.725
2.458	80.00	0.600	2.209	275.00	5.204	1.392	492.50	9.825
2.455	83.75	0.700	2.199	277.50	5.304	1.359	496.20	9.925
2.452	88.75	0.813	2.188	286.20	5.404	1.329	506.20	10.025
2.448	92.50	0.940	2.181	288.70	5.504	1.302	506.20	10.125
2.445	97.50	1.040	2.171	296.20	5.604	1.259	515.00	10.225
2.441	100.00	1.140	2.160	298.70	5.704	1.225	515.00	10.338
2.438	105.00	1.240	2.148	303.70	5.817	1.189	522.50	10.438
2.435	108.70	1.340	2.137	311.20	5.917	1.166	522.50	10.538
2.431	112.50	1.440	2.128	315.00	6.017	1.142	531.20	10.638
2.428	116.20	1.540	2.115	320.00	6.117	1.130	531.20	10.738
2.424	120.00	1.640	2.103	323.70	6.217	1.112	538.70	10.838
2.420	123.70	1.753	2.089	327.50	6.317	1.111	538.70	10.938
2.416	128.70	1.853	2.077	332.50	6.417	1.102	547.50	11.038
2.412	132.50	1.953	2.064	333.70	6.517	1.097	547.50	11.138
2.407	137.50	2.053	2.049	343.70	6.629	1.091	557.50	11.238
2.404	141.20	2.153	2.039	347.50	6.729	1.086	558.70	11.354
2.399	145.00	2.253	2.026	355.00	6.829	1.081	570.00	11.454
2.394	148.70	2.353	2.014	357.50	6.929	1.077	570.00	11.554
2.390	152.50	2.453	1.999	361.22	7.029	1.072	580.00	11.654
2.386	158.70	2.565	1.985	362.50	7.129	1.069	580.00	11.754

Table C.1 continued.

2.381	162.50	2.665	1.969	375.00	7.229	1.064	590.00	11.854
2.376	167.50	2.765	1.956	377.50	7.329	1.061	587.50	11.954
2.371	171.20	2.865	1.941	380.00	7.442	1.056	600.00	12.054
2.366	176.20	2.965	1.923	382.50	7.542	1.053	596.20	12.167
2.361	180.00	3.065	1.907	392.50	7.642	1.049	608.70	12.267
2.356	182.50	3.165	1.882	396.20	7.798	1.045	611.20	12.367
2.350	188.70	3.265	1.861	406.20	7.898	1.041	623.70	12.467
2.344	191.20	3.378	1.843	407.50	7.998	1.038	620.00	12.567
2.338	196.20	3.478	1.824	406.20	8.098	1.034	632.50	12.667
2.332	201.20	3.578	1.801	417.50	8.198	1.031	631.20	12.767
2.326	206.20	3.678	1.785	417.50	8.298	1.027	643.70	12.867
2.320	211.20	3.778	1.761	428.70	8.398	1.023	638.70	12.967
2.311	213.70	3.878	1.740	430.00	8.498	1.019	653.70	13.067
2.306	218.70	3.978	1.719	440.00	8.598	1.015	643.70	13.167
2.300	223.70	4.078	1.698	441.20	8.712	1.010	665.00	13.284
2.292	227.50	4.191	1.673	440.00	8.812	1.007	676.20	13.384
2.285	231.20	4.291	1.644	452.50	8.912	1.003	668.70	13.484
2.278	238.70	4.391	1.622	456.20	9.012	0.999	683.70	13.584
2.271	242.50	4.491	1.593	453.70	9.112	0.995	672.50	13.684

Appendix D Matlab® Script

The following appendix presents the Matlab® (The Mathworks Inc., Natick, Massachusetts) script and the methods used in calculating the evaluation parameters used in Sections 3.4.2.1 and 4.2.

The initial script was used to calculate the peak pressures of each load cell and the total relative displacement of the displacement sensor. Please note that the algorithm shown is for one load cell and one displacement sensor only.

Initially, data from the test was saved as a matrix in a text file. Each array corresponded to the measured data from a sensor. The entire Matlab® (The Mathworks Inc., Natick, Massachusetts) script is not presented here, but relevant sections describing the algorithms and methods are presented for one load cell and displacement sensor.

```
data =ts20d_july22_8b;
```

Initially, the data from each test series was saved as text files. Each text file was imported into Matlab® (The Mathworks Inc., Natick, Massachusetts). The data from the text files was saved into the dummy matrix called ‘data’.

```
[datanum, numDataset]= size (data);

limit=datanum;
```

The indices of the matrix were determined using the ‘size’ function. The number of data points were saved into the variable ‘limit’.

```
count=1;
while count<limit+1
   if data(count,3)<.22;
     data(count,3)=0;
    count=count+1
end
```

To simplify further analysis, the loop function ‘while’ was used to filter out all data points below 0.22 V, which relates to approximately 97 N or 10 Kg.

```
dia1=.07493;
pr1=max((data(:,3)*444.8)/(1000*.25*dia1^2));
```

The maximum pressure ‘prl’ (in kPa) was determined for each load cell by converting the measure signal from voltage to force and dividing the by the interaction area of the load cells.

```
d1=10.744*power(data(:,7),6)
-139.08*power(data(:,7),5)
+716.5*power(data(:,7),4)
-900.1*power(data(:,7),3)
+2749*power(data(:,7),2)
-2065.8*data(:,7)+642.489;

df1b=46.387*d1+33.047;
```

The displacement in millimeters of the displacement sensor was calculated and stored in the variable ‘d1’, while the force on the sensor was calculated and stored in the variable df1b. Details concerning the displacement and force equations are found in Appendix C.

```
di1=sum(d1(1:500))/500;
df1=sum(d1(limit-500))/500;
d1total= max(d1);-di1;
```

The variables ‘di1’ and ‘df1’ determines the initial and final displacement of the sensor by averaging the first and last 500 data points. The maximum deflection was the maximum displacement minus the initial displacement.

The following script was used to calculate the total and maximum impulse from the measured data of each load cell. The impulse from each load cell was determined using numerical integration. Specifically, midpoint approximation was used to calculate the total area under each impact spike of the temporal force curve, given by the equation.

$$I = \sum \Delta t \left(\frac{\mathrm{Pr}_{i+1} + \mathrm{Pr}_{i}}{2} \right) \tag{D.1}$$

where

Δt = time interval (s),
Pr = pressure,
i = index increment

```
[p1,n1]=peakdetect(data(:,3));
```

The function ‘peakdetect’ (Murray, 2005) finds the indices of the peaks and troughs in and array of data and stores the values in the arrays ‘p’ and ‘n’.

```
s1=size(p1);
```

The size of the arrays ‘p’ an ‘n’ were determined and the magnitude stored in the variable‘s1’.

```
count=1;
counter=1;
while count<s1(1,1)
      counter=p1(count)-10;
  while counter<(p1(count)+10);
imp(counter)=.001*(.5*(data(counter,3)+data(counter+1,3)));
      counter=counter+1;
  end
  imax1(count)=sum(imp);
  clear imp
  count=count+1;
end
```

The algorithm shown is for one load cell only. The algorithm was repeated for each array of data. A double looping function was employed to perform the calculation. It was determined by inspection that a single force spike does not exceed a length of 20 data points. Thus, for each location defined by ‘s’, the area under the curve was calculated from ‘s-10’ to ‘s+10’.
The variable ‘imp’ calculates the area of an individual rectangle, while the impulse for each spike was found by summing the values in ‘imp’ into ‘imax’.

```
totalimpulse1=sum(imax1);
totalimpulse2=sum(imax2);
totalimpulse3=sum(imax3);
totalimpulse4=sum(imax4);
```

The total impulse under a curve was the sum of ‘imax’ – as defined by the variable ‘totalimpulse’.

```
maximpulse1=max(imax1);
maximpulse2=max(imax2);
maximpulse3=max(imax3);
maximpulse4=max(imax4);
```

The maximum impulse generated by an individual spike was then the maximum value of ‘imax’.

The duty cycle was determined using the interaction pressure frequency and the pulse width of the pressure spike. By first determining the pulse width of each pressure spike, the cycle frequency was calculated. The algorithm shown is for one load cell only.

```
a=p1(1)-10;
b=p1(end)+9;
```

The data range to be analyzed was limited to .01s before the first pressure peak (as defined by p1(1)) and .009s after the last pressure peak.

```
count=a;
counter=1;
while count<b;
   if data(count,3)==0;
      if data(count+1,3)>0;
         edge1(counter,1)=count;
         counter=counter+1;
      end
   end
   count=count+1;
end
```

The algorithm detects a rising and falling edge and stores the indices in the first array of the matrix ‘edge1’.

```
count=a;
counter=1;
while count<b
if data(count,3)>0
         if data(count+1,3)==0
         edge1(counter,2)=count+1;
         counter=counter+1;
      end
   end
       count=count+1;
    end
```

The falling edge of a pressure spike was detected, storing the indices in the second array of ‘edge1’.

```
edge1(:,3)=edge1(:,2)-edge1(:,1);
```

The individual pulse width for each pressure peak defined by ‘p1’ was determined by subtracting the indices for the rising and falling edge of each spike and stored in the third array of the ‘edge1’ matrix.

```
 a=size(edge1);
 count=1;

 while count<a(1,1)
   edge1(count,4)=edge1(count+1,1)-
edge1(count,1);
    count=count+1;
 end
```

The cycle time was determined by calculating the time between the rising edge of each pressure spike

```
cycle1=mean(edge1(:,4))
freq1=1/(cycle1);
```

The average cycle time and interaction pressure frequency were calculated.

```
 pa1=size(edge1);
 pulseavg1=mean(edge1(round(pa1(1,1)/2)-
5:round(pa1(1,1)/2)+5,3))/1000;
```

The average pulse width of the center 10 pulses was calculated.

The following script was used to calculate the interaction pressure threshold values at the 53.5 and 110.6 kPa levels.

```
pr(:,1)=(-data(:,3)*444.8)/(1000*.25*dia1^2);
pr(:,2)=(-data(:,4)*444.8)/(1000*.25*dia2^2);
pr(:,3)=(-data(:,5)*444.8)/(1000*.25*dia3^2);
pr(:,4)=(data(:,6)*444.8)/(1000*.25*dia4^2);
```

Measured data from each load cell was converted into pressures. The value was stored in the arrays ‘pr’.

```
for count=1:limit
   if pr(count,1)<55.3;
      pr(count,1)=0;
   end
   if pr(count,2)<55.;
       pr(count,2)=0;
   end
    if pr(count,3)<55.3;
       pr(count,3)=0;
   end
    if pr(count,4)<55.;
       pr(count,4)=0;
   end
       end
```

To simplify further analysis, the loop function ‘while’ was used to filter out all data points below 55.3 kPa.

```
[p1,n1]=peakdetect(pr(:,1));
[p2,n2]=peakdetect(pr(:,2));
[p3,n3]=peakdetect(pr(:,3));
[p4,n4]=peakdetect(pr(:,4));

s(1,:)=size(p1);
s(2,:)=size(p2);
s(3,:)=size(p3);
s(4,:)=size(p4);
```

The peakdetect (Murray, 2005) function was used to determine the location of each peak pressure value in the data. The number of peak interaction pressure values were determined and stored in the variable array ‘s’.

The algorithm was repeated for the 110 kPa threshold.

Appendix E   PMN Test Data

Tests were conducted on two deactivated PMN AP landmines borrowed from DRDC. The purpose of the tests was to determine the magnitude of deflection needed to actuate the landmines detonation mechanism.

The actuation displacement was determined by compressing the pressure pad while measuring the applied static force and displacement. An Instron Universal Testing Machine was used to compress the PMN, and measure the landmine deflection and force. A typical force/deflection curve of the PMN is shown in Figure E.1.

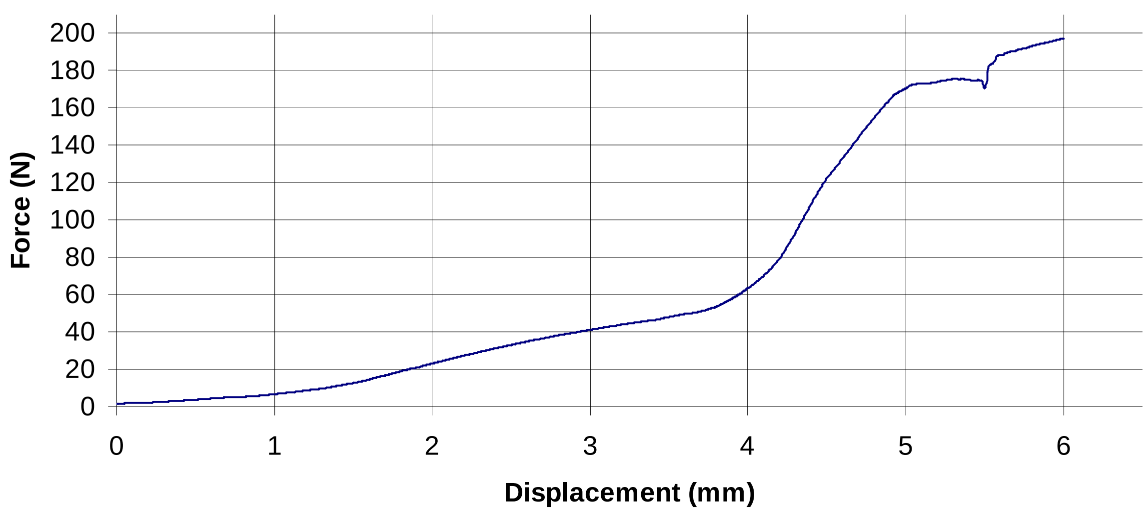


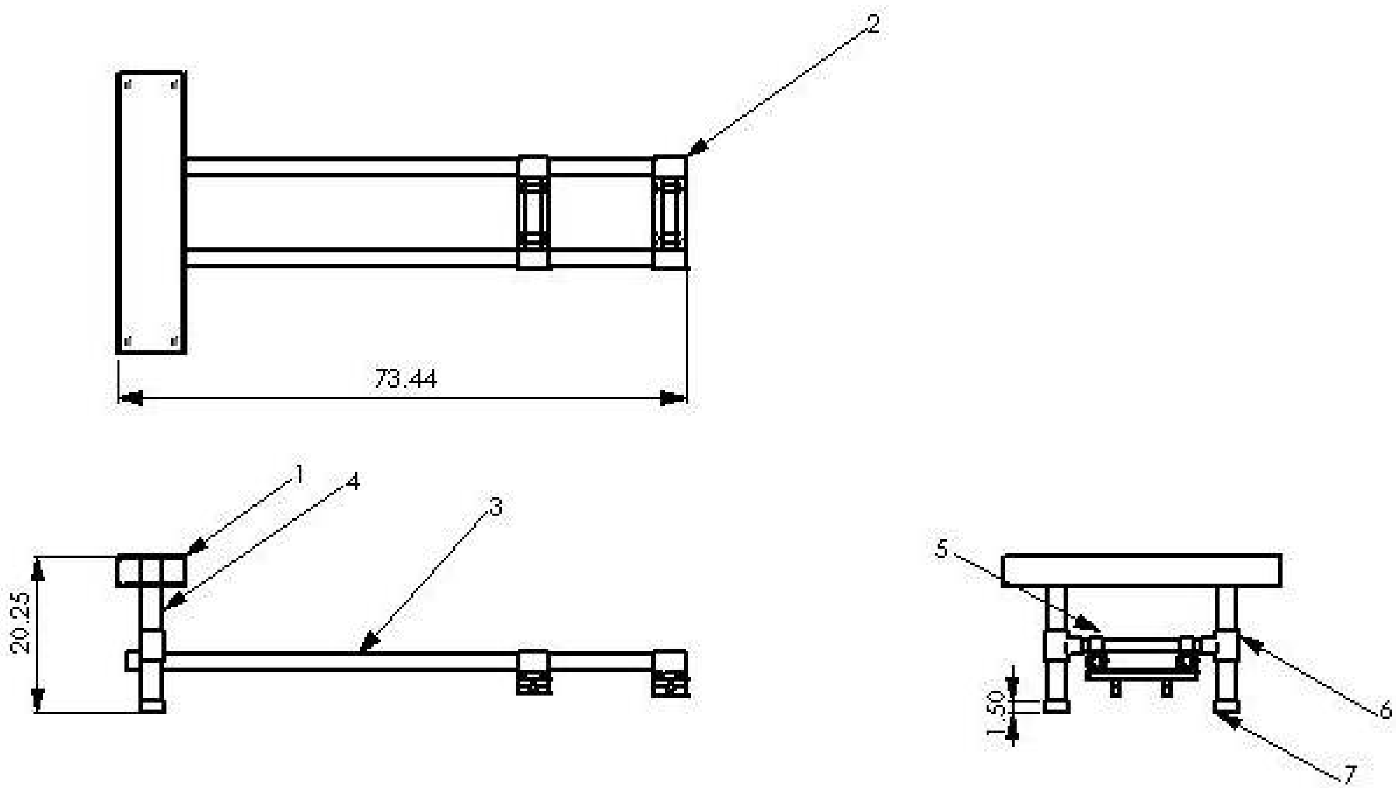
Figure E.1 Typical displacement profile of a PMN AP landmine.

It was determined that the deflection and static force needed to actuate the detonation mechanism was 5.9 mm and 144 N for a force applied at the center of the pressure plate. A displacement of 9.8 mm and a force of 84 N were needed for a force applied at the outer edge of the pressure plate.

Appendix F Test Rig Drawings

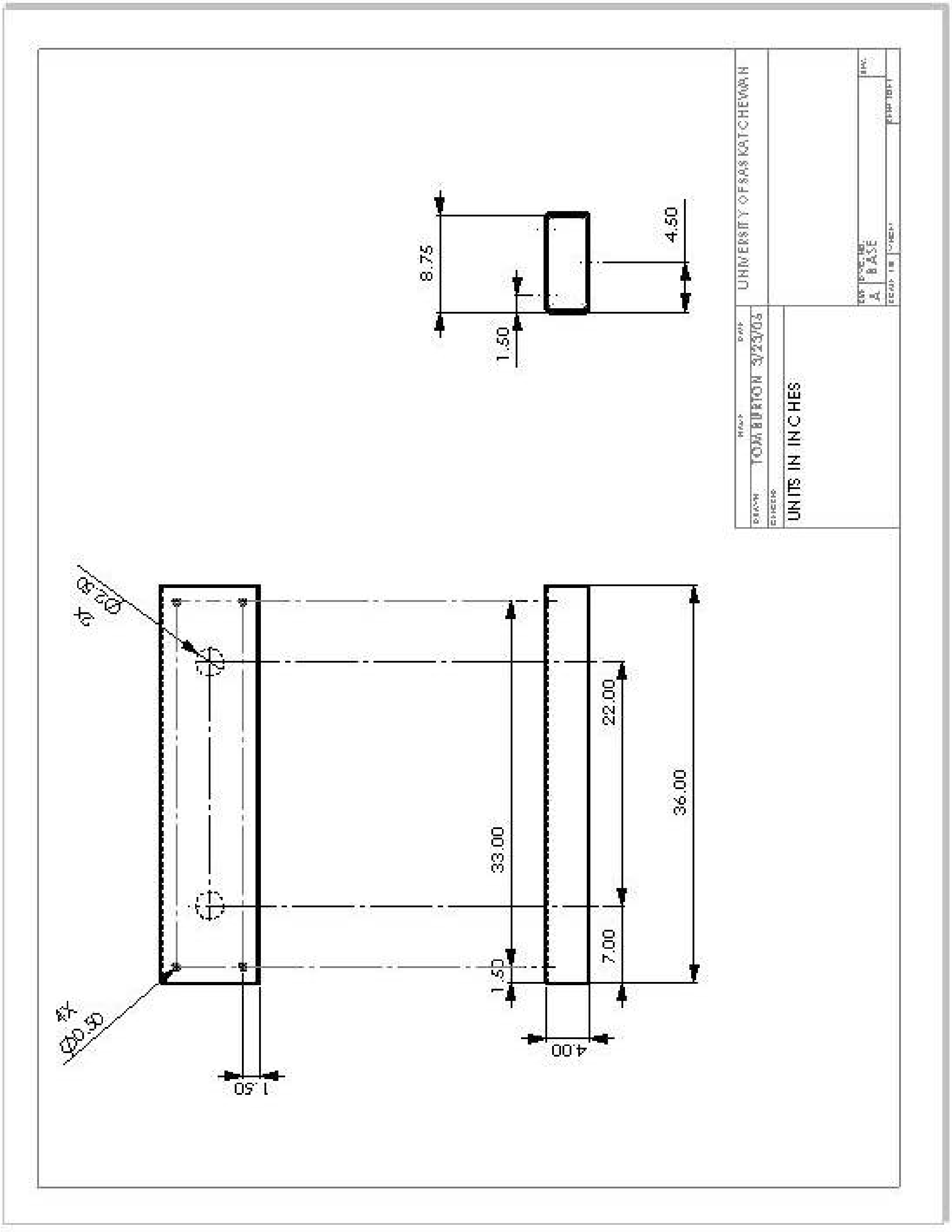
The following appendix presents the Test Rig schematics.

- Page 140– Total Assembly
- Page 141 – Base
- Page 142 – Swing Arm Assembly
- Page 143 – Extension Arm Cuff
- Page 144 – Vertical Slider Cuff
- Page 145 – Clamp Assembly

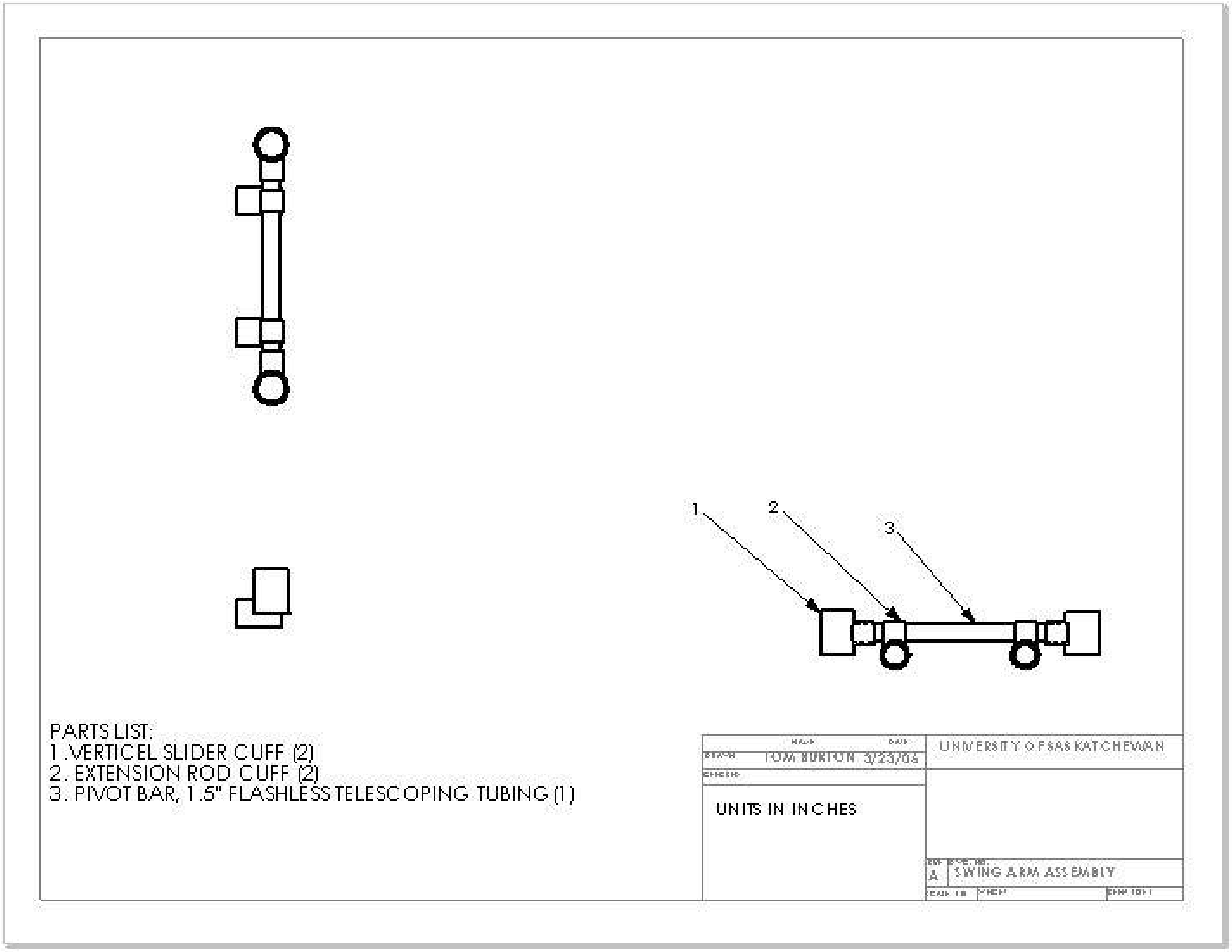


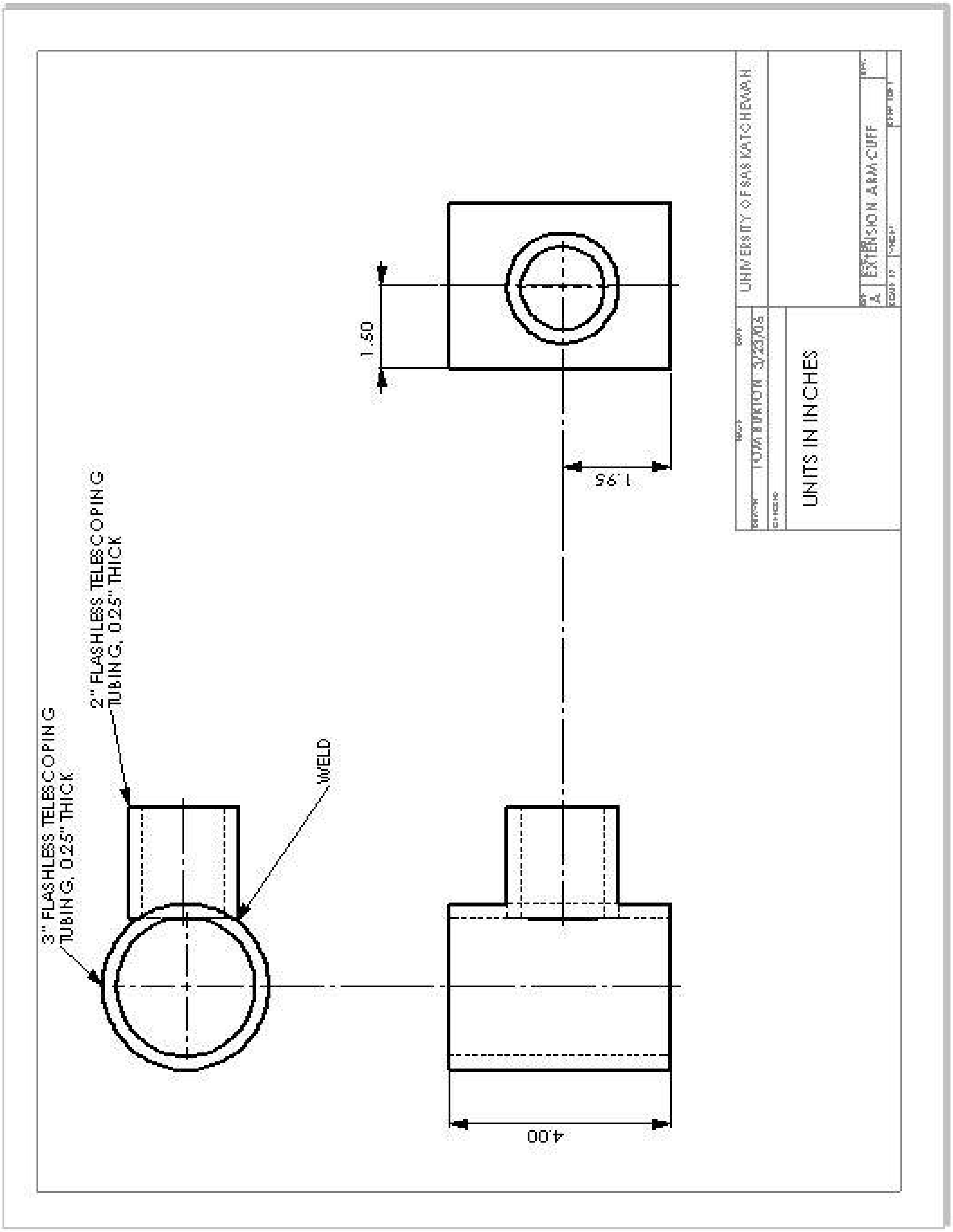
Parts list:
1. BASE (1)
2.CLAMP ASSEMBLY (2)
3 EXTENSION ROD, 2.5"FLASHLESS TELESCOPING TUBING, 1/4" THICK (2)
4.VERTICLE SLIDER ROD, 2.5"FLASHLESS TELESCOPING TUBING, 1/4" THI (2)
5. EXTENSION ARM CUFF (2)
6. VERTICLE SLIDER CUFF (2)
7.STOPPER, 3" FLASHLESS TELESCOPING TUBING, 1/4" THICK (2)

UNIVERSITY OF SASKATCHEWAN
TOM BURTON 3/23/06
UNITS IN INCHES
A TOTAL ASSEMBLY

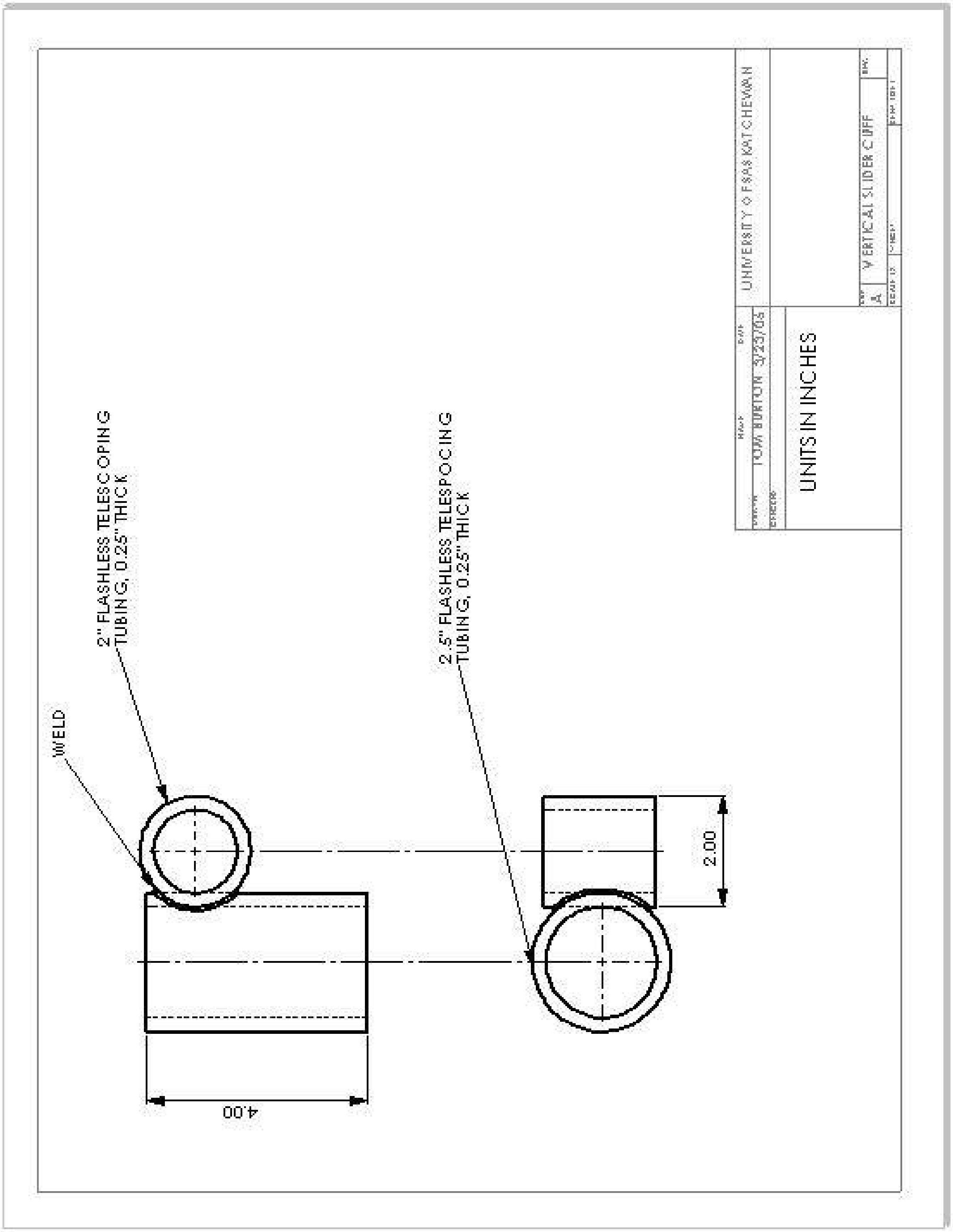


UNIVERSITY OF SASKATCHEWAN
TOM BURTON
UNITS IN INCHES
BASE
8.75
4.50
1.50
22.00
36.00
33.00
7.00
1.50
4.00
1.50
4X
Ø0.50
4X

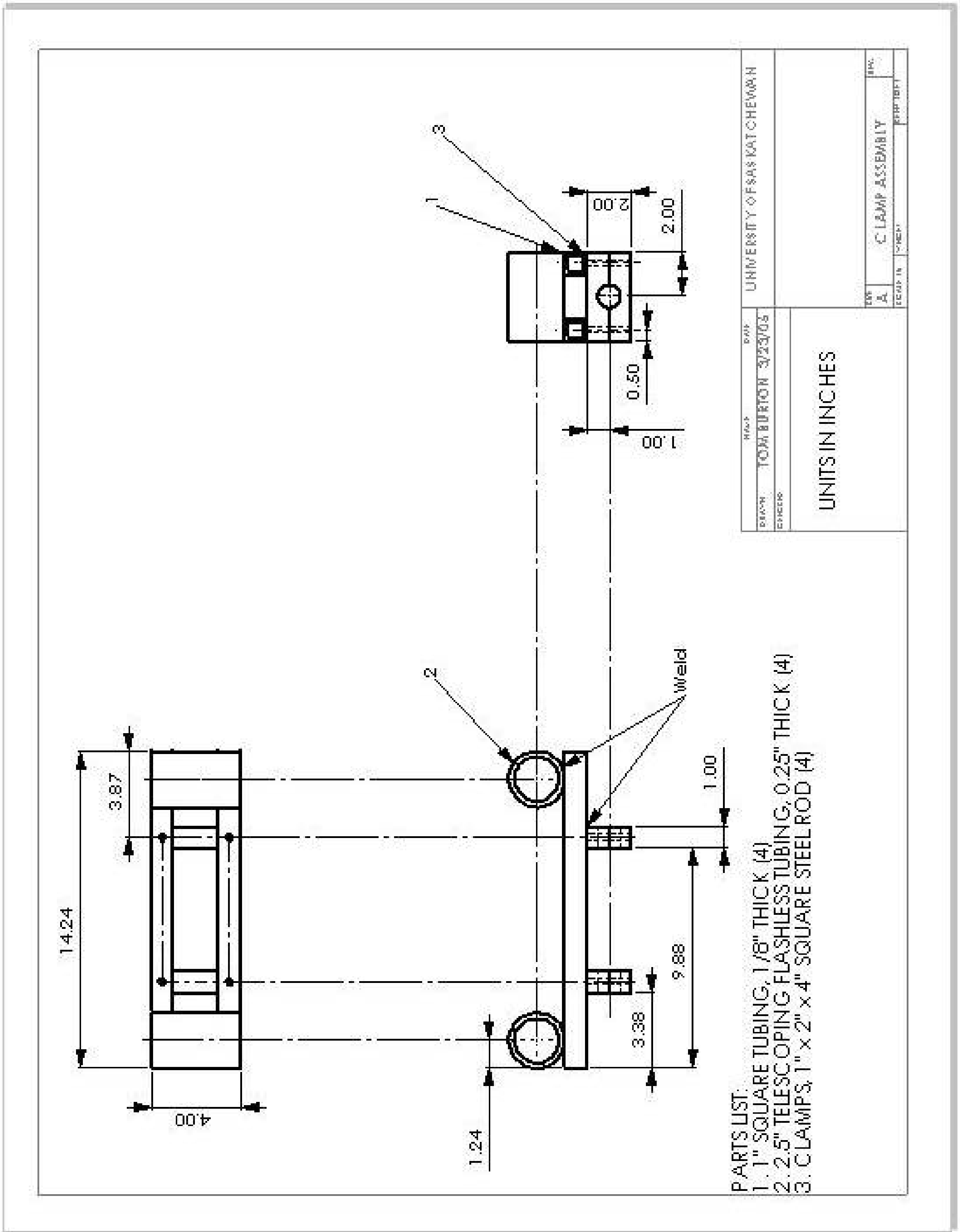

1
2
3
PARTS LIST:
1. VERTICEL SLIDER CUFF (2)
2. EXTENSION ROD CUFF (2)
3. PIVOT BAR, 1.5" FLASHLESS TELESCOPING TUBING (1)
TOM BURTON 3/23/06
UNITS IN INCHES
UNIVERSITY OF SASKATCHEWAN
A
SWING ARM ASSEMBLY



3" FLASHLESS TELESCOPING TUBING, 0.25" THICK
2" FLASHLESS TELESCOPING TUBING, 0.25" THICK
WELD
1.50
1.95
4.00
UNIVERSITY OF SASKATCHEWAN
TOM BURTON 3/23/06
UNITS IN INCHES
EXTENSION ARM CUFF



WELD
2" FLASHLESS TELESCOPING TUBING, 0.25" THICK
2.5" FLASHLESS TELESPOCING TUBING, 0.25" THICK
2.00
4.00
UNITS IN INCHES
VERTICAL SLIDER CUFF
A



PARTS LIST:
1. 1" SQUARE TUBING, 1/8" THICK (4)
2. 2.5" TELESCOPING FLASHLESS TUBING, 0.25" THICK (4)
3. CLAMPS, 1" x 2" x 4" SQUARE STEEL ROD (4)
14.24
3.87
4.00
1.24
3.38
9.88
1.00
Weld
2
1
3
2.00
2.00
0.50
1.00
UNIVERSITY OF SASKATCHEWAN
TOM BURTON 3/23/06
UNITS IN INCHES
A
C LAMP ASSEMBLY

Appendix G Raw Data

The following appendix presents the data set used in evaluation and statistical analysis as discussed in Section 4.3.1 *Results*. Table G.1 contains the calculated evaluation parameter values from each test run. Table G.2 presents the measured soil parameters from each test run.

Table G.1 Calculated evaluation parameters for each test run.

Test	Size	Load Cell	Interaction Pressure (kPa)	Sensor Displacement (mm)	Duty Cycle (%)	Total Impulse (Ns)	Max Impulse (Ns)	Interaction Threshold (110.6 kPa)	Interaction Threshold (110.6 kPa)
1a	1	1	316.2	6.6	9.8	173.8	5.88	68	59
2a	1	1	199.5	5.3	10.7	119.1	3.79		
3a	1	1	367.0	6.6	9.9	193.2	5.74	72	66
4a	1	1	230.5	4.4	10.1	108.9	3.77	62	53
5a	1	1	269.2	6.5		272.7	4.69		91
6a	1	1	234.4	9.2	11.5	173.5	4.62	74	64
7a	1	1	280.5	6.9	10.3	189.2	4.57	80	72
8a	1	1		8.3	9.0	73.5	5.20		
9a	1	1							
7a	1	2	389.8	6.6	9.5	202.4	5.49	69	64
8a	1	2	251.2	5.3	9.8	125.3	3.97	65	53
9a	1	2	307.4	6.6		174.8	4.09	83	73
1a	1	2	314.5	4.4	10.9	156.5	5.41		60
2a	1	2	250.0	6.5		270.1	4.44		90
3a	1	2	281.2	9.2	11.6	245.7	5.93	88	78
4a	1	2	342.6	6.9	10.3	232.4	5.58	80	74
5a	1	2	308.8	8.3	10.1	180.0	4.79	74	66
6a	1	2							
4a	1	3	364.7	6.6	9.4	199.1	5.24	73	65
5a	1	3	271.1	5.3	10.0	140.5	3.97	84	54
6a	1	3	355.4	6.6	9.0	176.9	5.26	75	66
7a	1	3	352.9	4.4	9.6	135.5	5.03	62	50
8a	1	3	280.0	6.5	11.0	265.9	4.82		89
9a	1	3	323.1	9.2	11.4	245.9	6.39	78	70
10a	1	3	287.6	6.9	10.5	206.0	5.04	79	74
11a	1	3	342.3	8.3	10.2	209.6	5.60	79	69
12a	1	3							
1a	2	1	459.8			312.9	8.65	74	67
2a	2	1							
3a	2	1	232.0		9.5	141.9	3.88	70	60
4a	2	1		8.3					
5a	2	1	245.8	8.1	9.4	120.6	4.04	31	28
6a	2	1	276.1	6.4	8.4	133.6	3.95	68	59

Table G.1 continued

7a	2	2	255.9		10.1	150.6	4.41	66	60
8a	2	2							91
9a	2	2	275.1		9.6	152.9	4.42	79	59
1a	2	2		8.3					
2a	2	2	273.6	8.1	9.1	128.2	4.20	74	53
3a	2	2	223.4	6.4	8.5	118.5	3.43	68	56
13a	2	3	287.6		8.9	222.0	4.54		88
14a	2	3						60	35
15a	2	3	304.4		9.9	175.1	4.94	66	59
10a	2	3		8.3					
11a	2	3	273.6	8.1	9.6	141.6	4.29	85	55
12a	2	3	277.3	6.4	8.6	151.9	4.16	68	60
1b	1	1	391.1	3.2	11.2	140.3	6.06	97	44
2b	1	1	204.2	2.9	9.1	99.6	3.15		
3b	1	1	504.4	6.9	10.0	237.7	8.48		66
4b	1	1	208.6	5.4	9.5	108.1	3.19	62	54
5b	1	1	360.1	6.6	11.5	203.1	5.66	68	63
6b	1	1	296.0	8.0	11.4	173.9	4.94	74	64
7b	1	1	359.8	5.8	11.4	198.0	5.88	68	61
8b	1	1	494.8	8.6		279.2	8.97		56
9b	1	1		9.0					
7b	1	2	471.6	3.2		119.5	6.48	48	39
8b	1	2	309.1	2.9	9.4	161.3	5.03	65	53
9b	1	2	392.8	6.9	7.9	164.1	5.24	85	73
1b	1	2	304.6	5.4	10.0	153.2	4.94	60	53
2b	1	2	345.5	6.6		196.0	5.16	70	64
3b	1	2	344.8	8.0		243.5	5.95	88	78
4b	1	2	455.1	5.8		271.0	7.23		68
5b	1	2	405.9	8.6			7.47		59
6b	1	2	420.6	9.0	9.8	170.7	6.73	67	59
4b	1	3	426.5	3.2	9.5	125.9	6.19	49	43
5b	1	3	300.0	2.9	9.2	139.6	4.51	84	54
6b	1	3	413.8	6.9	8.2	190.9	5.33	82	73
7b	1	3	326.8	5.4	9.0	142.4	4.41	58	51
8b	1	3	366.7	6.6	10.3	191.8	5.79	66	62
9b	1	3	421.6	8.0	11.7	248.3	6.88	78	70
10b	1	3	377.0	5.8	10.4	214.8	5.74	78	65
11b	1	3	419.2	8.6	9.0	213.7	6.73	82	60
12b	1	3	370.1	9.0	10.6	200.8	5.69	72	64
1b	2	1				300.9			65
2b	2	1	358.8		7.8	148.1	5.17	73	64
3b	2	1	295.5		9.1	143.0	4.32	61	56
4b	2	1	368.9	6.9	9.1	165.6	5.36	59	55
5b	2	1	283.5	6.2	8.8	123.0	4.35	55	50
6b	2	1	338.9	5.0	8.8	137.4	4.95	63	52
7b	2	2	313.5		9.0	151.3	4.65	58	52
8b	2	2	351.2		8.4	218.4	4.23		
9b	2	2	366.7		8.6	144.2	4.95	58	53

Table G.1 continued

1b	2	2	397.2	6.9		321.6			60
2b	2	2	336.4	6.2	9.4	143.2	4.85	60	56
3b	2	2	281.5	5.0	8.7	126.8	4.10	63	55
13b	2	3	363.0		9.1	158.3	4.94	64	57
14b	2	3	452.7		7.8	243.2	5.47	90	
15b	2	3	418.2		10.5	200.1	5.81		55
10b	2	3	433.9	6.9	8.6	179.3	6.06	88	56
11b	2	3	368.4	6.2	9.0	168.1	5.05	78	62
12b	2	3	338.2	5.0	8.6	147.9	4.91	75	57
1c	1	1	468.7	1.7	10.6	200.0	7.26		58
2c	1	1	256.1	3.2	1.0	104.7	4.45	73	52
3c	1	1	504.4	8.0	1.1	201.0	8.15		56
4c	1	1	216.7	3.3	10.0	90.0	3.34	58	48
5c	1	1	415.7	6.2	9.2	188.1	6.52	94	63
6c	1	1	282.2	3.7	9.4	112.3	5.45	60	53
7c	1	1	388.1	4.6	10.1	176.0	6.53	71	62
8c	1	1	369.9	8.1	10.9	197.3	6.18	72	60
9c	1	1	186.2		8.9	53.3	2.68	42	
7c	1	2	504.4	1.7	8.1	148.9	7.62	63	55
8c	1	2	360.3	3.2	1.6	133.3	6.05	76	54
9c	1	2	362.0	8.0	1.1	107.6	4.11	62	56
1c	1	2	277.3	3.3	10.8	128.6	4.64		57
2c	1	2	397.7	6.2	8.0	186.1	6.24	93	64
3c	1	2	307.6	3.7	10.9	186.0	4.99	96	67
4c	1	2	480.0	4.6	10.1		6.66		
5c	1	2	415.2	8.1		256.6	7.47		54
6c	1	2	357.6		10.4	178.5	5.85		54
4c	1	3	500.9	1.7	7.4	154.2	7.10	63	55
5c	1	3	324.8	3.2	1.0	131.6	4.90	88	53
6c	1	3	452.9	8.0	7.6	131.8	6.13	62	55
7c	1	3	306.6	3.3	8.0	97.7	4.08	65	47
8c	1	3	470.4	6.2	9.0	178.3	7.40	68	60
9c	1	3	402.9	3.7	9.4	180.4	5.78	77	60
10c	1	3	400.9	4.6	9.4	224.8	5.40	90	
11c	1	3	457.1	8.1	8.0	189.1	6.56	77	56
12c	1	3	369.9		9.7	164.6	5.89	88	53
1c	2	1	504.4		10.3			61	53
2c	2	1	414.2		7.5	110.0	5.69	55	50
3c	2	1	303.7		8.7	130.7	4.33	73	58
4c	2	1	324.3	6.3		140.8	4.58	95	59
5c	2	1	322.1	5.9	7.0	120.7	4.42	86	59
6c	2	1	365.2	5.3	7.6	116.2	5.38	64	43
7c	2	2	305.1		9.7	130.9	4.31	62	52
8c	2	2	405.1		7.9	143.8	4.63	86	62
9c	2	2	397.5		9.3	144.1	5.17	83	56
1c	2	2	433.5	6.3					76
2c	2	2	367.2	5.9	8.5	162.7	5.09	77	58
3c	2	2	325.8	5.3	7.9	98.5	4.84	50	43

Table G.1 continued

13c	2	3	299.7		8.5	104.3	4.05	54	45
14c	2	3	489.4		6.7	155.4	5.79	94	60
15c	2	3	440.8		8.8	182.9	5.57		58
10c	2	3	504.4	6.3	9.1	181.5	7.63	91	55
11c	2	3	414.2	5.9	7.7	137.4	5.09	85	60
12c	2	3	377.8	5.3	8.1		5.54	74	48

Table G.2 Measured soil parameters

Test	Pass	Size	Load Cell	Initial CI	Final CI	Sensor Depth (cm)	Moisture Content (%)
1a	1	S	1	617	1510	210	7.6
2a	1	S	1	360	3227	185	7.6
3a	1	S	1	318	4603	195	8.0
4a	1	S	1	373	2955	195	8.0
5a	1	S	1	607	2248	210	11.5
6a	1	S	1	567	2820	200	11.5
7a	1	S	1	676	2955	205	10.7
8a	1	S	1	380	3159	185	10.7
9a	1	S	1	523	3052	205	11.8
1a	1	S	2	622	1544	190	7.6
2a	1	S	2	210	3207	170	7.6
3a	1	S	2	229	3798	205	8.0
4a	1	S	2	424	4438	205	8.0
5a	1	S	2	597	3566	215	11.5
6a	1	S	2	590	3779	210	11.5
7a	1	S	2		3430	200	10.7
8a	1	S	2	397	3081	195	10.7
9a	1	S	2	839	3556	205	11.8
1a	1	S	3	491		180	7.6
2a	1	S	3	296	3236	175	7.6
3a	1	S	3	264	4428	195	8.0
4a	1	S	3	380	3915	185	8.0
5a	1	S	3	572	2965	200	11.5
6a	1	S	3	434	2490	210	11.5
7a	1	S	3	530	2616	205	10.7
8a	1	S	3	599	3721	200	10.7
9a	1	S	3	493	1986	220	11.8
1a	1	S	4	587	1606	200	7.6
2a	1	S	4	197	3866	185	7.6
3a	1	S	4	355	2510	200	8.0
4a	1	S	4	350	3304	180	8.0
5a	1	S	4	459	3130	210	11.5
6a	1	S	4	444	2655	200	11.5
7a	1	S	4	750	3401	195	10.7
8a	1	S	4	474	2752	190	10.7
9a	1	S	4	461	2762	190	11.8

Table G.2 continued

1a	1	S	5	617	1544	200	7.6
2a	1	S	5		4167	185	7.6
3a	1	S	5	530	3488	200	8.0
4a	1	S	5	580	4273	180	8.0
5a	1	S	5		3479	210	11.5
6a	1	S	5	484	2510	200	11.5
7a	1	S	5	442	3672	195	10.7
8a	1	S	5	442	3149	190	10.7
9a	1	S	5	725	1773	190	11.8
10a	1	B	1	336	2674	205	8.7
11a	1	B	1	555	2258	205	8.7
12a	1	B	1	629	3266	215	8.7
13a	1	B	1	444	3295	200	5.7
14a	1	B	1	429	3023	190	5.7
15a	1	B	1	540	3643	205	5.7
10a	1	B	2	743	2645	200	8.7
11a	1	B	2	493	2083	200	8.7
12a	1	B	2	639	3159	200	8.7
13a	1	B	2	624	3924	205	5.7
14a	1	B	2	397	2229	195	5.7
15a	1	B	2	308	3004	215	5.7
10a	1	B	3	493	3634	205	8.7
11a	1	B	3	558	1986	195	8.7
12a	1	B	3	530	3343	200	8.7
13a	1	B	3	627	2936	190	5.7
14a	1	B	3	321	3401	190	5.7
15a	1	B	3	540	2849	205	5.7
10a	1	B	4	377	1938	215	8.7
11a	1	B	4	624	2258	0	8.7
12a	1	B	4		2364	0	8.7
13a	1	B	4	560	3014	195	5.7
14a	1	B	4	311	2645	175	5.7
15a	1	B	4	410	3760	195	5.7
10a	1	B	5	582	1899	215	8.7
11a	1	B	5	454	2229	0	8.7
12a	1	B	5	461	3401	0	8.7
13a	1	B	5	385	2694	195	5.7
14a	1	B	5	479	2820	175	5.7
15a	1	B	5	540	2984	195	5.7
1b	2	S	1	1510	1579	170	7.6
2b	2	S	1	3227	6153	155	7.6
3b	2	S	1	4603	4787	150	8.0
4b	2	S	1	2955	43178	165	8.0
5b	2	S	1	2248	3295	170	11.5
6b	2	S	1	2820	4603	175	11.5
7b	2	S	1	2955	5087	165	10.7
8b	2	S	1	3159	5068	145	10.7
9b	2	S	1	3052	3275	165	11.8

Table G.2 continued

1b	2	S	2	1544	1520	150	7.6
2b	2	S	2	3207	5368	150	7.6
3b	2	S	2	3798	5669	160	8.0
4b	2	S	2	4438	4273	155	8.0
5b	2	S	2	3566	4041	165	11.5
6b	2	S	2	3779	5359	160	11.5
7b	2	S	2	3430	3537	155	10.7
8b	2	S	2	3081	4516	150	10.7
9b	2	S	2	3556	4516	170	11.8
1b	2	S	3		1525	140	7.6
2b	2	S	3	3236	4409	150	7.6
3b	2	S	3	4428	5339	155	8.0
4b	2	S	3	3915	5426	160	8.0
5b	2	S	3	2965	4583	155	11.5
6b	2	S	3	2490	4312	155	11.5
7b	2	S	3	2616	4264	150	10.7
8b	2	S	3	3721	5010	155	10.7
9b	2	S	3	1986	3275	185	11.8
1b	2	S	4	1606	1525	150	7.6
2b	2	S	4	3866	4409	140	7.6
3b	2	S	4	2510	4942	170	8.0
4b	2	S	4	3304	3711	150	8.0
5b	2	S	4	3130	4264	165	11.5
6b	2	S	4	2655	4457	150	11.5
7b	2	S	4	3401	3924	145	10.7
8b	2	S	4	2752	3924	150	10.7
9b	2	S	4	2762	4574	150	11.8
1b	2	S	5	1544	1537	150	7.6
2b	2	S	5	4167	5174	140	7.6
3b	2	S	5	3488	4884	170	8.0
4b	2	S	5	4273	4399	150	8.0
5b	2	S	5	3479	4419	165	11.5
6b	2	S	5	2510	4748	150	11.5
7b	2	S	5	3672	4331	145	10.7
8b	2	S	5	3149	4128	150	10.7
9b	2	S	5	1773		150	11.8
10b	2	B	1	2674	2674	160	8.7
11b	2	B	1	2258	4651	150	8.7
12b	2	B	1	3266	3818	165	8.7
13b	2	B	1	3295	3576	165	5.7
14b	2	B	1	3023	3217	145	5.7
15b	2	B	1	3643	3479	165	5.7
10b	2	B	2	2645	3488	160	8.7
11b	2	B	2	2083	4360	145	8.7
12b	2	B	2	3159	3769	145	8.7
13b	2	B	2	3924	4884	170	5.7
14b	2	B	2	2229	4690	145	5.7
15b	2	B	2	3004	4002	165	5.7

Table G.2 continued

10b	2	B	3	3634	3953	155	8.7
11b	2	B	3	1986	4283	150	8.7
12b	2	B	3	3343	4118	150	8.7
13b	2	B	3	2936	3798	155	5.7
14b	2	B	3	3401	3101	140	5.7
15b	2	B	3	2849	4496	160	5.7
10b	2	B	4	1938	2955	165	8.7
11b	2	B	4	2258	3605	0	8.7
12b	2	B	4	2364	4215	0	8.7
13b	2	B	4	3014	4797	160	5.7
14b	2	B	4	2645	3450	125	5.7
15b	2	B	4	3760	4089	160	5.7
10b	2	B	5	1899	2994	165	8.7
11b	2	B	5	2229	4244	0	8.7
12b	2	B	5	3401	3992	0	8.7
13b	2	B	5	2694	5572	160	5.7
14b	2	B	5	2820	3314	125	5.7
15b	2	B	5	2984	4700	160	5.7
1c	3	S	1	1579	1586	160	7.6
2c	3	S	1	6153	5087	145	7.6
3c	3	S	1	4787	4360	140	8.0
4c	3	S	1	43178	5736	160	8.0
5c	3	S	1	3295	5213	155	11.5
6c	3	S	1	4603	5659	140	11.5
7c	3	S	1	5087	4186	155	10.7
8c	3	S	1	5068	4777	135	10.7
9c	3	S	1	3275	3992	150	11.8
1c	3	S	2	1520	1446	140	7.6
2c	3	S	2	5368	4050	140	7.6
3c	3	S	2	5669	5039	150	8.0
4c	3	S	2	4273	5862	150	8.0
5c	3	S	2	4041	4787	155	11.5
6c	3	S	2	5359	5523	150	11.5
7c	3	S	2	3537	6240	140	10.7
8c	3	S	2	4516	5000	140	10.7
9c	3	S	2	4516	5078	155	11.8
1c	3	S	3	1525	1695	130	7.6
2c	3	S	3	4409	5504	140	7.6
3c	3	S	3	5339	6502	145	8.0
4c	3	S	3	5426	4845	150	8.0
5c	3	S	3	4583	4719	140	11.5
6c	3	S	3	4312	4845	140	11.5
7c	3	S	3	4264	4797	140	10.7
8c	3	S	3	5010	5097	145	10.7
9c	3	S	3	3275	4448	165	11.8
1c	3	S	4	1525	1655	145	7.6
2c	3	S	4	4409	4864	135	7.6
3c	3	S	4	4942	6269	150	8.0

Table G.2 continued

4c	3	S	4	3711	5678	145	8.0
5c	3	S	4	4264	5746	150	11.5
6c	3	S	4	4457	7267	135	11.5
7c	3	S	4	3924	5814	135	10.7
8c	3	S	4	3924	4419	140	10.7
9c	3	S	4	4574	2984	140	11.8
1c	3	S	5	1537	1493	145	7.6
2c	3	S	5	5174	4874	135	7.6
3c	3	S	5	4884	5814	150	8.0
4c	3	S	5	4399	5407	145	8.0
5c	3	S	5	4419	5756	150	11.5
6c	3	S	5	4748	5455	135	11.5
7c	3	S	5	4331	4457	135	10.7
8c	3	S	5	4128	5814	140	10.7
9c	3	S	5		3924	140	11.8
10c	3	B	1	2674	2762	155	8.7
11c	3	B	1	4651	4874	140	8.7
12c	3	B	1	3818	5165	155	8.7
13c	3	B	1	3576	4419	150	5.7
14c	3	B	1	3217	4176	130	5.7
15c	3	B	1	3479	5921	155	5.7
10c	3	B	2	3488	3895	145	8.7
11c	3	B	2	4360	6298	130	8.7
12c	3	B	2	3769	2810	130	8.7
13c	3	B	2	4884	6076	155	5.7
14c	3	B	2	4690	5649	135	5.7
15c	3	B	2	4002	4341	160	5.7
10c	3	B	3	3953	4438	150	8.7
11c	3	B	3	4283	3973	130	8.7
12c	3	B	3	4118	5329	135	8.7
13c	3	B	3	3798	6405	145	5.7
14c	3	B	3	3101	5320	130	5.7
15c	3	B	3	4496	6686	150	5.7
10c	3	B	4	2955	3382	155	8.7
11c	3	B	4	3605	4884	0	8.7
12c	3	B	4	4215		0	8.7
13c	3	B	4	4797	4845	150	5.7
14c	3	B	4	3450	4351	115	5.7
15c	3	B	4	4089	6521	155	5.7
10c	3	B	5	2994	5068	155	8.7
11c	3	B	5	4244	5300	0	8.7
12c	3	B	5	3992	5252	0	8.7
13c	3	B	5	5572	6541	150	5.7
14c	3	B	5	3314	6066	115	5.7
15c	3	B	5	4700	6056	155	5.7

Appendix H Statistical Analysis

A statistical analysis of the measured parameters was performed to determine the effects of the operational parameters pass, load cell base area, and tamper shoe size on the evaluation parameters used in Chapter 4 *Final Design Evaluation and Testing*. The analysis was performed per pass, using a one-way analysis of variance (ANOVA) at a 5% level of significance. The following appendix presents the outputted raw data from the statistical software Minitab® (Minitab Inc., State College, Pennsylvania).

The most important value in the analysis of variance table outputted from software was the p-value. The p-value indicates whether the level means were significantly different from each other (Minitab, 2005). A p-value less than or equal to the level of significance (in this case 5%) indicates that one or more means were significantly different.

Interaction Pressure

Pass 1, Small Shoe, Load Cells 1 to 4

```
Source   DF  SS     MS     F      P
LC(1,s)   3  11087  3696  1.93  0.150
Error    26  49831  1917
Total    29  60917
S = 43.78   R-Sq = 18.20%   R-Sq(adj) = 8.76%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev   -+---------+---------+---------+--------
1      7  271.05  56.91   (----------*-----------)
2      8  305.69  46.61               (----------*----------)
3      8  322.16  37.49                     (---------*----------)
4      7  314.86  29.87                  (----------*----------)
                          -+---------+---------+---------+--------
                         240       270       300       330
Pooled StDev = 43.78
```

Pass 1, Big Shoe, Load Cells 1 to 4

```
Source   DF     SS    MS     F      P
LC(1,b)   3   8134  2711  0.72  0.562
Error    11  41524  3775
Total    14  49658
S = 61.44   R-Sq = 16.38%   R-Sq(adj) = 0.00%
```

```
                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level  N    Mean   StDev   ---+---------+---------+---------+------
1      4  303.41  105.86             (-----------*----------)
2      4  256.99   24.05      (----------*----------)
3      4  285.74   13.79          (-----------*----------)
4      3  242.56   52.91   (------------*------------)
                           ---+---------+---------+---------+------
                             180       240       300       360
Pooled StDev = 61.44
```

Pass 1, Big and Small Shoe, Load Cells 1-4

```
Source       DF      SS    MS     F      P
Size(1,a&b)   1    8993  8993  3.50  0.068
Error        43  110575  2572
Total        44  119568
S = 50.71   R-Sq = 7.52%   R-Sq(adj) = 5.37%

                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level   N    Mean  StDev   ------+---------+---------+---------+---
1      30  304.14  45.83                     (--------*--------)
2      15  274.15  59.56   (------------*------------)
                           ------+---------+---------+---------+---
                                260       280       300       320
Pooled StDev = 50.71
```

Pass 2, Small Shoe, Load Cells 1-4

```
Source    DF      SS    MS     F      P
LCR(2,s)   3    5064  1688  0.31  0.820
Error     30  164895  5496
Total     33  169959
S = 74.14   R-Sq = 2.98%   R-Sq(adj) = 0.00%

                                Individual 95% CIs For Mean Based on
                                Pooled StDev
Level  N    Mean   StDev   -----+---------+---------+---------+----
1      8  352.36  113.90   (---------------*--------------)
2      9  383.34   60.78             (--------------*-------------)
3      9  380.19   44.85            (--------------*-------------)
4      8  366.58   63.74       (---------------*--------------)
                           -----+---------+---------+---------+----
                              315       350       385       420
Pooled StDev = 74.14
```

Pass 2, Big Shoe, Load Cells 1-4

```
Source   DF     SS    MS     F      P
LC(2,b)   3  23312  7771  2.21  0.118
Error    20  70325  3516
Total    23  93637
S = 59.30   R-Sq = 24.90%   R-Sq(adj) = 13.63%
```

```
                        Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  --------+---------+---------+---------+-
1      6  358.33  79.21            (---------*---------)
2      6  341.08  40.61        (---------*---------)
3      6  395.72  45.46                   (---------*---------)
4      6  309.37  63.84  (---------*---------)
                         --------+---------+---------+---------+-
                              300       350       400       450
Pooled StDev = 59.30
```

Pass 2, Big and Small Shoe, Load Cells 1-4

```
Source       DF      SS    MS     F      P
Size(2,a&b)   1    7031  7031  1.72  0.195
Error        54  220835  4090
Total        55  227866
S = 63.95   R-Sq = 3.09%   R-Sq(adj) = 1.29%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev   -+---------+---------+---------+--------
1      33  367.24  68.85                (-----------*----------)
2      23  344.46  56.06   (------------*-------------)
                           -+---------+---------+---------+--------
                          320       340       360       380
Pooled StDev = 63.95
```

Pass 3, Small Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
LC(3,s)   3   20491  6830  0.85  0.475
Error    30  239805  7993
Total    33  260296
S = 89.41   R-Sq = 7.87%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ----+---------+---------+---------+-----
1      9  343.11  112.73  (------------*-----------)
2      9  384.68   74.02           (-----------*-----------)
3      9  409.60   66.75                (-----------*-----------)
4      7  373.45   98.89       (-------------*------------)
                          ----+---------+---------+---------+-----
                            300       350       400       450
Pooled StDev = 89.41
```

Pass 3, Big Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
LC(3,b)   3   22660  7553  1.45  0.259
Error    20  104496  5225
Total    23  127156
S = 72.28   R-Sq = 17.82%   R-Sq(adj) = 5.49%
```

```
                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level  N    Mean  StDev  -----+---------+---------+---------+----
1      6  372.32  75.87         (---------*---------)
2      6  372.37  49.29         (---------*---------)
3      6  421.05  75.69                 (---------*---------)
4      6  334.48  83.58  (----------*---------)
                         -----+---------+---------+---------+----
                            300       360       420       480
Pooled StDev = 72.28
```

Pass 3, Big and Small Shoe, Load Cells 1-4

```
Source       DF      SS    MS     F      P
Size(3,1-3)   1     964   964  0.15  0.703
Error        43  280503  6523
Total        44  281467
S = 80.77   R-Sq = 0.34%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ------+---------+---------+---------+---
B      18  388.58  68.19   (-----------------*------------------)
S      27  379.13  88.02  (---------------*--------------)
                          ------+---------+---------+---------+---
                              360       380       400       420
Pooled StDev = 80.77
```

Pass 1 to 3, Small Shoe, Load Cells 1-4

```
Source           DF       SS     MS      F      P
Pass(all,1234)    2   198991  99495  18.99  0.000
Error           159   833065   5239
Total           161  1032055
S = 72.38   R-Sq = 19.28%   R-Sq(adj) = 18.27%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --+---------+---------+---------+-------
1      45  294.14  52.13  (-----*-----)
2      59  367.00  74.96                       (----*----)
3      58  376.76  82.46                         (-----*----)
                          --+---------+---------+---------+-------
                          280       315       350       385
Pooled StDev = 72.38
```

Pass 1 to 3, Big Shoe

```
Source  DF      SS     MS      F      P
C10      2   97279  48639  10.79  0.000
Error   60  270450   4507
Total   62  367728
S = 67.14   R-Sq = 26.45%   R-Sq(adj) = 24.00%
```

```
                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --+---------+---------+---------+-------
1      15  274.15  59.56  (------*------)
2      24  351.13  63.81                   (----*-----)
3      24  375.05  74.35                        (----*----)
                          --+---------+---------+---------+-------
                          250       300       350       400
Pooled StDev = 67.14
```

Displacement

Pass 1, Big and Small Shoe

```
Source  DF     SS    MS     F      P
Size     1   1.75  1.75  0.85  0.379
Error    9  18.38  2.04
Total   10  20.13
S = 1.429   R-Sq = 8.67%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  ----+---------+---------+---------+-----
B      3  7.600  1.042   (-----------------*------------------)
S      8  6.706  1.522  (----------*----------)
                        ----+---------+---------+---------+-----
                          6.0       7.0       8.0       9.0
Pooled StDev = 1.429
```

Pass 2, Big and Small Shoe

```
Source  DF     SS    MS     F      P
Size_2   1   0.15  0.15  0.04  0.849
Error   10  40.24  4.02
Total   11  40.39
S = 2.006   R-Sq = 0.38%   R-Sq(adj) = 0.00%
```

```
                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  -------+---------+---------+---------+--
B      3  6.010  0.971  (----------------*----------------)
S      9  6.271  2.190           (---------*---------)
                        -------+---------+---------+---------+--
                             4.5       6.0       7.5       9.0
Pooled StDev = 2.006
```

Pass 3, Big and Small Shoe

```
Source  DF     SS    MS     F      P
Size_3   1   2.04  2.04  0.46  0.516
Error    9  40.07  4.45
Total   10  42.10
S = 2.110   R-Sq = 4.84%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev    +---------+---------+---------+---------
B      3  5.820  0.474    (------------------*------------------)
S      8  4.854  2.379     (-----------*-----------)
                          +---------+---------+---------+---------
                        3.0       4.5       6.0       7.5
Pooled StDev = 2.110
```

Pass1-3, Small

```
Source  DF      SS    MS     F      P
C21      2   15.11  7.56  1.77  0.195
Error   22   94.18  4.28
Total   24  109.30
S = 2.069   R-Sq = 13.83%   R-Sq(adj) = 5.99%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  --------+---------+---------+---------+-
a      8  6.706  1.522               (---------*---------)
b      9  6.271  2.190            (---------*--------)
c      8  4.854  2.379  (---------*---------)
                        --------+---------+---------+---------+-
                              4.5       6.0       7.5       9.0
Pooled StDev = 2.069
```

Pass1-3,b

```
Source  DF      SS     MS     F      P
C26      2   5.733  2.867  3.82  0.085
Error    6   4.505  0.751
Total    8  10.239
S = 0.8665   R-Sq = 56.00%   R-Sq(adj) = 41.33%
```

```
                              Individual 95% CIs For Mean Based on
                              Pooled StDev
Level  N    Mean   StDev  --+---------+---------+---------+-------
a      3  7.6002  1.0415                 (---------*----------)
b      3  6.0105  0.9713    (---------*---------)
c      3  5.8198  0.4739  (---------*----------)
                          --+---------+---------+---------+-------
                          4.8       6.0       7.2       8.4
Pooled StDev = 0.8665
```

Duty Cycle

Pass 1, Small Shoe, Load Cells 1 to 4

```
Source   DF      SS     MS     F      P
LC(a,s)   3  11.044  3.681  4.24  0.014
Error    26  22.564  0.868
Total    29  33.609
S = 0.9316   R-Sq = 32.86%   R-Sq(adj) = 25.12%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean  StDev  --+---------+---------+---------+-------
1      7  10.161  0.775  (--------*--------)
2      8  10.361  1.169     (--------*-------)
3      8  10.140  0.797  (--------*-------)
4      7  11.643  0.907                  (---------*--------)
                         --+---------+---------+---------+-------
                         9.60     10.40     11.20     12.00
Pooled StDev = 0.932
```

Pass 1, Big Shoe, Load Cells 1 to 4

```
Source   DF     SS    MS     F      P
LC(a,b)   3   3.77  1.26  0.95  0.452
Error    11  14.60  1.33
Total    14  18.37
S = 1.152   R-Sq = 20.51%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on Pooled
                          StDev
Level  N    Mean  StDev    +---------+---------+---------+---------
1      4  10.031  1.897           (-----------*------------)
2      4   9.307  0.659    (------------*------------)
3      4   9.253  0.570    (------------*-----------)
4      3  10.500  0.874             (--------------*--------------)
                           +---------+---------+---------+---------
                         8.0       9.0      10.0      11.0
Pooled StDev = 1.152
```

Pass 1, Big and Small Shoe

Load Cells 1 to 4

```
Source          DF     SS    MS     F      P
Size(a,a&b)_1    1   8.09  8.09  6.37  0.015
Error           44  55.88  1.27
Total           45  63.97
S = 1.127   R-Sq = 12.65%   R-Sq(adj) = 10.67%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  -------+---------+---------+---------+--
1      31  10.619  1.118                      (-------*--------)
2      15   9.724  1.146  (----------*-----------)
                          -------+---------+---------+---------+--
                              9.50     10.00     10.50     11.00
Pooled StDev = 1.127
```

Load Cells 1 to 3

```
Source        DF      SS     MS     F      P
Size(a,a&b)    1   3.786  3.786  3.85  0.058
Error         33  32.446  0.983
Total         34  36.232
S = 0.9916   R-Sq = 10.45%   R-Sq(adj) = 7.74%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev   -+---------+---------+---------+--------
1      23  10.223  0.901                     (-------*--------)
2      12   9.530  1.151   (-----------*----------)
                           -+---------+---------+---------+--------
                          9.00      9.50     10.00     10.50
Pooled StDev = 0.992
```

Pass 2, Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
LC(b,s)   3   69.82  23.27  3.85  0.021
Error    27  163.29   6.05
Total    30  233.11
S = 2.459   R-Sq = 29.95%   R-Sq(adj) = 22.17%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  --------+---------+---------+---------+-
1      7  10.582  1.023             (---------*--------)
2      8   8.248  4.527  (--------*--------)
3      9   9.764  1.065          (--------*-------)
4      7  12.487  0.864                      (--------*---------)
                         --------+---------+---------+---------+-
                              8.0      10.0      12.0      14.0
Pooled StDev = 2.459
```

Pass 2, Big Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
LC(b,b)   3  11.130  3.710  6.65  0.004
Error    16   8.924  0.558
Total    19  20.054
S = 0.7468   R-Sq = 55.50%   R-Sq(adj) = 47.16%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev    +---------+---------+---------+---------
1      5   8.728  0.539    (------*------)
2      5   8.813  0.390     (------*------)
3      6   8.928  0.881       (-----*------)
4      4  10.685  1.044                       (-------*-------)
                           +---------+---------+---------+---------
                         8.0       9.0      10.0      11.0
Pooled StDev = 0.747
```

Pass 2, Big and Small Shoe

Load Cells 1-4

```
Source     DF      SS     MS     F      P
Size(b)_1   1   11.48  11.48  2.22  0.143
Error      49  253.16   5.17
Total      50  264.64
S = 2.273   R-Sq = 4.34%   R-Sq(adj) = 2.38%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --------+---------+---------+---------+-
b      20   9.201  1.027  (------------*------------)
s      31  10.172  2.788                 (---------*---------)
                          --------+---------+---------+---------+-
                                8.80      9.60     10.40     11.20
Pooled StDev = 2.273
```

Load Cells 1-3

```
Source   DF      SS    MS     F      P
Size(b)   1    4.28  4.28  0.87  0.356
Error    38  185.95  4.89
Total    39  190.23
S = 2.212   R-Sq = 2.25%   R-Sq(adj) = 0.00%


                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev    +---------+---------+---------+---------
b      16  8.830  0.620    (---------------*---------------)
s      24  9.497  2.799                (------------*------------)
                           +---------+---------+---------+---------
                         7.70      8.40      9.10      9.80
Pooled StDev = 2.212
```

Pass 3, Small Shoe, Load Cells 1-4

```
Source   DF     SS    MS     F      P
LC(c,s)   3  179.2  59.7  2.84  0.057
Error    26  546.0  21.0
Total    29  725.2
S = 4.583   R-Sq = 24.71%   R-Sq(adj) = 16.02%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ---------+---------+---------+---------+
1      9   7.905  3.942   (-------*-------)
2      8   7.638  4.054  (-------*-------)
3      9   7.727  2.658  (-------*-------)
4      4  14.945  9.130                (----------*-----------)
                         ---------+---------+---------+---------+
                               8.0      12.0      16.0      20.0
Pooled StDev = 4.583
```

Pass3,Big Shoe, Load Cells 1-4

```
Source   DF     SS    MS     F      P
LC(c,b)   3  22.10  7.37  6.59  0.004
Error    17  19.00  1.12
Total    20  41.11
S = 1.057   R-Sq = 53.77%   R-Sq(adj) = 45.61%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev    +---------+---------+---------+---------
1      5   8.230  1.341    (--------*-------)
2      5   8.657  0.832        (-------*-------)
3      6   8.151  0.857    (-------*-------)
4      5  10.700  1.159                         (-------*-------)
                           +---------+---------+---------+---------
                         7.2       8.4       9.6      10.8
Pooled StDev = 1.057
```

Pass 3, Big and Small Shoe

Load Cells 1-4

```
Source   DF     SS    MS     F      P
Size(c)   1    0.4   0.4  0.03  0.874
Error    48  766.3  16.0
Total    49  766.7
S = 3.996   R-Sq = 0.05%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ---------+---------+---------+---------+
b      21  8.897  1.434  (-----------------*-----------------)
s      29  8.715  5.089   (--------------*--------------)
                         ---------+---------+---------+---------+
                               8.0       9.0      10.0      11.0
Pooled StDev = 3.996
```

Load Cells 1-3

```
Source      DF     SS    MS     F      P
Size(c)_1    1    0.4   0.4  0.03  0.875
Error       49  766.3  15.6
Total       50  766.7
S = 3.955   R-Sq = 0.05%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  --------+---------+---------+---------+-
b      21  8.897  1.434  (----------------*----------------)
s      30  8.719  5.001   (-------------*--------------)
                         --------+---------+---------+---------+-
                               8.0       9.0      10.0      11.0
Pooled StDev = 3.955
```

Pass 1 to 3, Small Shoe, Load Cells 1-4

```
Source  DF      SS     MS     F      P
C57      2   79.40  39.70  5.62  0.005
Error   70  494.29   7.06
Total   72  573.69
S = 2.657   R-Sq = 13.84%   R-Sq(adj) = 11.38%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
a      23  10.223  0.901                    (--------*--------)
b      24   9.497  2.799              (--------*--------)
c      26   7.761  3.442  (--------*-------)
                          ----+---------+---------+---------+-----
                            7.2       8.4       9.6      10.8
Pooled StDev = 2.657
```

Pass 1 to 3, Big Shoe, Load Cells 1-3

```
Source  DF      SS     MS     F      P
C63      2   9.823  4.911  5.79  0.006
Error   41  34.754  0.848
Total   43  44.576
S = 0.9207   R-Sq = 22.04%   R-Sq(adj) = 18.23%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ---------+---------+---------+---------+
a      12  9.530  1.151                    (--------*--------)
b      16  8.830  0.620          (-------*-------)
c      16  8.334  0.980  (-------*-------)
                         ---------+---------+---------+---------+
                               8.40      9.00      9.60     10.20
Pooled StDev = 0.921
```

Total Impulse

Pass 1, Small Shoe, Load Cells 1 to

```
Source   DF     SS    MS     F      P
LC(a,s)   3  11066  3689  1.52  0.233
Error    27  65667  2432
Total    30  76733
S = 49.32   R-Sq = 14.42%   R-Sq(adj) = 4.91%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ----+---------+---------+---------+-----
1      8  162.97  61.77  (----------*---------)
2      8  198.40  48.60            (----------*---------)
3      8  197.41  45.91            (---------*----------)
4      7  215.25  35.74                 (---------*----------)
                         ----+---------+---------+---------+-----
                           140       175       210       245
Pooled StDev = 49.32
```

Pass 1, Big Shoe, Load Cells 1 to 4

```
Source   DF     SS    MS     F      P
LC(a,b)   3   5899  1966  0.66  0.594
Error    11  32833  2985
Total    14  38732
S = 54.63   R-Sq = 15.23%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -------+---------+---------+---------+--
1      4  177.24  90.87            (-----------*-----------)
2      4  137.57  16.90    (------------*-----------)
3      4  172.63  35.74            (-----------*-----------)
4      3  132.66  41.07  (-------------*-----------)
                         -------+---------+---------+---------+--
                              100       150       200       250
Pooled StDev = 54.63
```

Pass 1, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
Size(a)   1   13316  13316  5.07  0.029
Error    44  115465   2624
Total    45  128782
S = 51.23   R-Sq = 10.34%   R-Sq(adj) = 8.30%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --------+---------+---------+---------+-
B      15  156.51  52.60  (----------*---------)
S      31  192.81  50.57                   (------*-------)
                          --------+---------+---------+---------+-
                                150       175       200       225
Pooled StDev = 51.23
```

Pass 2, Small Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
LC(b,s)   3    6412  2137  0.60  0.618
Error    28   99183  3542
Total    31  105595
S = 59.52   R-Sq = 6.07%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev   -+---------+---------+---------+--------
1      8  179.98  62.40   (-----------*------------)
2      9  204.44  74.93           (----------*-----------)
3      9  185.35  40.95     (-----------*-----------)
4      6  217.25  52.14            (-------------*-------------)
                          -+---------+---------+---------+--------
                         140       175       210       245
Pooled StDev = 59.52
```

Pass 2, Big Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
LC(b,b)   3   27434   9145  0.91  0.455
Error    20  201571  10079
Total    23  229006
S = 100.4   R-Sq = 11.98%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  --------+---------+---------+---------+-
1      6  169.7   65.8  (-----------*-----------)
2      6  184.3   74.4    (-----------*------------)
3      6  182.8   34.6    (-----------*-----------)
4      6  255.9  171.0            (------------*-----------)
                        --------+---------+---------+---------+-
                              140       210       280       350
Pooled StDev = 100.4
```

Pass 2, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
Size(b)   1    9658   9658  0.68  0.413
Error    56  794037  14179
Total    57  803695
S = 119.1   R-Sq = 1.20%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev    +---------+---------+---------+---------
B      24  198.1   99.8    (---------------*---------------)
S      34  224.3  130.9               (-------------*------------)
                           +---------+---------+---------+---------
                         150       180       210       240
Pooled StDev = 119.1
```

Pass 3, Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
LC(c,s)   3   32347  10782  1.98  0.140
Error    27  146902   5441
Total    30  179249
S = 73.76   R-Sq = 18.05%   R-Sq(adj) = 8.94%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ---+---------+---------+---------+------
1      8  154.09   56.28  (--------*--------)
2      9  183.09   68.07       (--------*-------)
3      9  161.40   37.60   (--------*-------)
4      5  248.96  138.16              (----------*-----------)
                          ---+---------+---------+---------+------
                           120       180       240       300
Pooled StDev = 73.76
```

Pass 3, Big Shoe, Load Cells 1-4

```
Source   DF     SS   MS     F      P
LC(c,b)   3   2025  675  1.05  0.396
Error    17  10929  643
Total    20  12954
S = 25.36   R-Sq = 15.63%   R-Sq(adj) = 0.74%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev   +---------+---------+---------+---------
1      5  123.66  12.19   (-----------*-----------)
2      5  136.00  23.84         (-----------*-----------)
3      6  147.04  32.13                (----------*---------)
4      5  124.45  26.93   (-----------*-----------)
                          +---------+---------+---------+---------
                         100       120       140       160
Pooled StDev = 25.36
```

Pass 3, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
SIze(c)   1   27031  27031  7.03  0.011
Error    50  192203   3844
Total    51  219234
S = 62.00   R-Sq = 12.33%   R-Sq(adj) = 10.58%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  -------+---------+---------+---------+--
B      21  133.47  25.45  (---------*----------)
S      31  179.93  77.30                    (--------*--------)
                          -------+---------+---------+---------+--
                               125       150       175       200
Pooled StDev = 62.00
```

Pass 1 to 3, Small Shoe, Load Cells 1-4

```
Source  DF      SS    MS     F      P
PASS     2    7323  3661  1.08  0.343
Error   88  297770  3384
Total   90  305093
S = 58.17   R-Sq = 2.40%   R-Sq(adj) = 0.18%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
a      30  196.78  46.25                (------------*------------)
b      31  190.02  50.78            (------------*------------)
c      30  175.20  73.90  (------------*-------------)
                          ----+---------+---------+---------+-----
                            160       176       192       208
Pooled StDev = 58.17
```

Pass 1 to 3, Big Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
Pass(b)   2   48334  24167  4.91  0.011
Error    57  280692   4924
Total    59  329026
S = 70.17   R-Sq = 14.69%   R-Sq(adj) = 11.70%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev   -+---------+---------+---------+--------
a      15  156.51  52.60       (----------*---------)
b      24  198.15  99.78                     (--------*-------)
c      21  133.47  25.45   (--------*--------)
                           -+---------+---------+---------+--------
                          105       140       175       210
Pooled StDev = 70.17
```

Maximum Impulse

Pass 1, Small Shoe, Load Cells 1 to 4

```
Source   DF      SS     MS     F      P
LC(a,s)   3   3.589  1.196  2.56  0.076
Error    27  12.640  0.468
Total    30  16.229
S = 0.6842   R-Sq = 22.12%   R-Sq(adj) = 13.46%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ----+---------+---------+---------+-----
1      8  4.7817  0.7927  (---------*---------)
2      8  4.9622  0.7426     (---------*---------)
3      8  5.1685  0.6844         (---------*---------)
4      7  5.7136  0.4287                    (---------*----------)
                          ----+---------+---------+---------+-----
                            4.50      5.00      5.50      6.00
Pooled StDev = 0.6842
```

Pass 1, Big Shoe, Load Cells 1 to 4

```
Source   DF     SS    MS     F      P
LC(a,b)   3   2.65  0.88  0.50  0.689
Error    11  19.35  1.76
Total    14  22.00
S = 1.326   R-Sq = 12.04%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev   +---------+---------+---------+---------
1      4  5.129  2.348              (-----------*-----------)
2      4  4.114  0.468     (-----------*-----------)
3      4  4.483  0.345        (-----------*------------)
4      3  4.103  0.950   (-------------*-------------)
                         +---------+---------+---------+---------
                        2.4       3.6       4.8       6.0
Pooled StDev = 1.326
```

Pass 1, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
Size(a)   1   4.378  4.378  5.04  0.030
Error    44  38.196  0.868
Total    45  42.573
S = 0.9317   R-Sq = 10.28%   R-Sq(adj) = 8.24%

                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean   StDev   +---------+---------+---------+---------
B      15  4.4804  1.2526   (-----------*-----------)
S      31  5.1385  0.7355                       (-------*--------)
                            +---------+---------+---------+---------
                           4.00      4.40      4.80      5.20
Pooled StDev = 0.9317
```

Pass 2, Small Shoe, Load Cells 1-4

```
Source   DF     SS    MS     F      P
LC(b,s)   3   6.60  2.20  1.21  0.324
Error    30  54.71  1.82
Total    33  61.31
S = 1.350   R-Sq = 10.77%   R-Sq(adj) = 1.84%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev   +---------+---------+---------+---------
1      8  5.790  2.136   (-----------*------------)
2      9  6.026  0.985       (----------*-----------)
3      9  5.696  0.859   (----------*-----------)
4      8  6.836  1.141                (-----------*------------)
                         +---------+---------+---------+---------
                        4.80      5.60      6.40      7.20
Pooled StDev = 1.350
```

Pass 2, Big Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
LC(b,b)   3   3.884  1.295  1.44  0.264
Error    18  16.158  0.898
Total    21  20.043
S = 0.9475   R-Sq = 19.38%   R-Sq(adj) = 5.94%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  --------+---------+---------+---------+-
1      5  4.8311  0.4757      (------------*------------)
2      5  4.5564  0.3779  (------------*------------)
3      6  5.3732  0.4873               (-----------*----------)
4      6  5.6195  1.6429                   (----------*-----------)
                          --------+---------+---------+---------+-
                               4.20      4.90      5.60      6.30
Pooled StDev = 0.9475
```

Pass 2, Big and Small Shoe, Load Cells 1-4

```
Source   DF     SS     MS     F      P
Size(b)   1  11.85  11.85  7.87  0.007
Error    54  81.36   1.51
Total    55  93.21
S = 1.227   R-Sq = 12.72%   R-Sq(adj) = 11.10%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  --------+---------+---------+---------+-
B      22  5.132  0.977  (----------*---------)
S      34  6.074  1.363                      (-------*--------)
                         --------+---------+---------+---------+-
                              5.00      5.50      6.00      6.50
Pooled StDev = 1.227
```

Pass 3, Small Shoe, Load Cells 1-4

```
Source   DF     SS    MS     F      P
LC(c,s)   3  17.49  5.83  2.47  0.081
Error    30  70.77  2.36
Total    33  88.26
S = 1.536   R-Sq = 19.82%   R-Sq(adj) = 11.80%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  --+---------+---------+---------+-------
1      9  5.617  1.815  (--------*--------)
2      9  5.958  1.211     (--------*-------)
3      9  5.917  1.045     (-------*--------)
4      7  7.573  1.997               (---------*---------)
                        --+---------+---------+---------+-------
                        4.8       6.0       7.2       8.4
Pooled StDev = 1.536
```

Pass 3, Big Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
LC(c,b)   3   2.288  0.763  1.31  0.305
Error    17   9.936  0.584
Total    20  12.224
S = 0.7645   R-Sq = 18.72%   R-Sq(adj) = 4.38%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  --+---------+---------+---------+-------
1      5  4.8802  0.6137   (-----------*-----------)
2      5  4.8081  0.3498  (-----------*-----------)
3      6  5.6114  1.1682                 (----------*---------)
4      5  4.9984  0.5284     (-----------*-----------)
                          --+---------+---------+---------+-------
                          4.20      4.80      5.40      6.00
Pooled StDev = 0.7645
```

Pass 3, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
SIze(c)   1   15.40  15.40  8.12  0.006
Error    53  100.48   1.90
Total    54  115.89
S = 1.377   R-Sq = 13.29%   R-Sq(adj) = 11.66%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  -----+---------+---------+---------+----
B      21  5.100  0.782  (---------*---------)
S      34  6.189  1.635                      (-------*-------)
                         -----+---------+---------+---------+----
                           4.80      5.40      6.00      6.60
Pooled StDev = 1.377
```

Pass 1 to 3, Small Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
PASS(s)   2   18.03  9.02  5.71  0.005
Error    94  148.34  1.58
Total    96  166.37
S = 1.256   R-Sq = 10.84%   R-Sq(adj) = 8.94%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
a      30  5.136  0.748  (--------*--------)
b      34  6.074  1.363                   (-------*--------)
c      33  6.065  1.487                   (-------*--------)
                         ------+---------+---------+---------+---
                            5.00      5.50      6.00      6.50
Pooled StDev = 1.256
```

Pass 1 to 3, Big Shoe, Load Cells 1-4

```
Source    DF      SS     MS     F      P
Pass(b)    2   4.501  2.250  2.28  0.112
Error     55  54.271  0.987
Total     57  58.772
S = 0.9934   R-Sq = 7.66%   R-Sq(adj) = 4.30%

                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean   StDev  -+---------+---------+---------+--------
a      15  4.4807  1.2537   (------------*------------)
b      22  5.1315  0.9769                    (---------*----------)
c      21  5.1001  0.7818                   (----------*---------)
                            -+---------+---------+---------+--------
                           4.00      4.40      4.80      5.20
Pooled StDev = 0.9934
```

Threshold Level 53.3 kPa

Pass 1, Small Shoe, Load Cells 1 to 4

```
Source  DF     SS    MS     F      P
C1       2   87.9  43.9  0.77  0.480
Error   15  853.7  56.9
Total   17  941.6
S = 7.544   R-Sq = 9.33%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  --+---------+---------+---------+-------
1      5  71.200  6.723  (-------------*--------------)
2      6  76.500  8.735              (------------*-----------)
3      7  75.714  6.969             (-----------*-----------)
                          --+---------+---------+---------+-------
                         65.0      70.0      75.0      80.0
Pooled StDev = 7.544
```

Pass 1, Big Shoe, Load Cells 1 to 4

```
Source  DF     SS    MS     F      P
C5       2    8.0   4.0  0.07  0.934
Error    8  468.2  58.5
Total   10  476.2
S = 7.650   R-Sq = 1.68%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ---------+---------+---------+---------+
1      3  70.667   3.055  (----------------*----------------)
2      4  71.750   5.909      (--------------*-------------)
3      4  69.750  10.720   (-------------*--------------)
                          ---------+---------+---------+---------+
                                66.0      72.0      78.0      84.0
Pooled StDev = 7.650
```

Pass 1, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
C50       1    54.7  54.7  0.92  0.349
Error    23  1373.3  59.7
Total    24  1428.0
S = 7.727   R-Sq = 3.83%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  ---+---------+---------+---------+------
B       7  71.429  8.482  (----------------*----------------)
S      18  74.722  7.442                (---------*----------)
                          ---+---------+---------+---------+------
                          66.5      70.0      73.5      77.0
Pooled StDev = 7.727
```

Pass 2, Small Shoe, Load Cells 1-4

```
Source   DF    SS   MS     F      P
C14       2    74   37  0.21  0.809
Error    18  3082  171
Total    20  3155
S = 13.08   R-Sq = 2.33%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  ------+---------+---------+---------+---
1      5  73.80  13.65      (----------------*-----------------)
2      7  69.00  13.90  (--------------*-------------)
3      9  72.11  12.13        (------------*------------)
                        ------+---------+---------+---------+---
                           63.0      70.0      77.0      84.0
Pooled StDev = 13.08
```

Pass 2, Big Shoe, Load Cells 1-4

```
Source   DF      SS     MS     F      P
C18       2  1042.0  521.0  8.93  0.005
Error    11   641.6   58.3
Total    13  1683.5
S = 7.637   R-Sq = 61.89%   R-Sq(adj) = 54.96%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ---------+---------+---------+---------+
1      5  62.200   6.723      (------*-------)
2      4  59.750   2.363  (--------*-------)
3      5  79.000  10.536                     (-------*-------)
                          ---------+---------+---------+---------+
                                  60        70        80        90
Pooled StDev = 7.637
```

Pass 2, Big and Small Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C56      1   133  133  0.91  0.348
Error   33  4839  147
Total   34  4972
S = 12.11   R-Sq = 2.67%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  --------+---------+---------+---------+-
B      14  67.50  11.38  (----------------*---------------)
S      21  71.48  12.56              (-------------*------------)
                         --------+---------+---------+---------+-
                              64.0      68.0      72.0      76.0
Pooled StDev = 12.11
```

Pass 3, Small Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C22      2   413  206  1.02  0.379
Error   18  3627  201
Total   20  4040
S = 14.19   R-Sq = 10.22%   R-Sq(adj) = 0.25%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  ----+---------+---------+---------+-----
1      7  67.14  16.13  (----------*----------)
2      5  78.00  16.08           (------------*------------)
3      9  75.33  11.36           (---------*---------)
                        ----+---------+---------+---------+-----
                           60        70        80        90
Pooled StDev = 14.19
```

Pass 3, Big Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C26      2   200  100  0.41  0.672
Error   13  3178  244
Total   15  3378
S = 15.63   R-Sq = 5.92%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  ----+---------+---------+---------+-----
1      6  72.33  15.49     (------------*-------------)
2      5  71.60  15.21  (---------------*--------------)
3      5  79.60  16.23          (---------------*--------------)
                        ----+---------+---------+---------+-----
                           60        70        80        90
Pooled StDev = 15.63
```

Pass 3, Big and Small Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C62      1    12   12  0.06  0.815
Error   35  7418  212
Total   36  7429
S = 14.56   R-Sq = 0.16%   R-Sq(adj) = 0.00%

                         Individual 90% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ------+---------+---------+---------+---
B      16  74.37  15.01   (----------------*-----------------)
S      21  73.24  14.21  (--------------*---------------)
                         ------+---------+---------+---------+---
                            70.0      73.5      77.0      80.5
Pooled StDev = 14.56
```

Pass 1 to 3, Small Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C31      2   103   52  0.36  0.699
Error   57  8137  143
Total   59  8240
S = 11.95   R-Sq = 1.25%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ----+---------+---------+---------+-----
a      18  74.72   7.44         (-------------*-------------)
b      21  71.48  12.56  (------------*------------)
c      21  73.24  14.21      (------------*------------)
                         ----+---------+---------+---------+-----
                          68.0      72.0      76.0      80.0
Pooled StDev = 11.95
```

Pass 1 to 3, Big Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C37      2   354  177  1.22  0.308
Error   38  5537  146
Total   40  5892
S = 12.07   R-Sq = 6.02%   R-Sq(adj) = 1.07%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  --------+---------+---------+---------+-
a      11  70.73   6.90       (-------------*--------------)
b      14  67.50  11.38  (------------*------------)
c      16  74.37  15.01                 (-----------*-----------)
                         --------+---------+---------+---------+-
                              65.0      70.0      75.0      80.0
Pooled StDev = 12.07
```

Threshold Level 2

Pass 1, Small Shoe, Load Cells 1 to 4

```
Source  DF    SS   MS     F      P
C1       2    31   16  0.11  0.900
Error   19  2808  148
Total   21  2839
S = 12.16   R-Sq = 1.11%   R-Sq(adj) = 0.00%

                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level  N   Mean  StDev  -----+---------+---------+---------+----
1      6  67.50  13.19  (----------------*-----------------)
2      8  69.75  11.52        (--------------*--------------)
3      8  67.13  12.01    (--------------*--------------)
                        -----+---------+---------+---------+----
                           60.0      66.0      72.0      78.0
Pooled StDev = 12.16
```

Pass 1, Big Shoe, Load Cells 1 to 4

```
Source  DF    SS   MS     F      P
C5       2   236  118  0.39  0.684
Error   11  3293  299
Total   13  3529
S = 17.30   R-Sq = 6.68%   R-Sq(adj) = 0.00%

                        Individual 95% CIs For Mean Based on
                        Pooled StDev
Level  N   Mean  StDev  -+---------+---------+---------+--------
1      4  53.50  17.37  (---------------*--------------)
2      5  63.80  15.45            (-------------*-------------)
3      5  59.40  18.93        (-------------*--------------)
                        -+---------+---------+---------+--------
                        36        48        60        72
Pooled StDev = 17.30
```

Pass 1, Big and Small Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C50      1   262  262  1.44  0.240
Error   29  5273  182
Total   30  5535
S = 13.48   R-Sq = 4.73%   R-Sq(adj) = 1.45%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev   --+---------+---------+---------+-------
B       9  61.78  17.44   (--------------*--------------)
S      22  68.18  11.63                  (---------*--------)
                          --+---------+---------+---------+-------
                         54.0      60.0      66.0      72.0
Pooled StDev = 13.48
```

Pass 2, Small Shoe, Load Cells 1-4

```
Source  DF      SS    MS     F      P
C14      2    24.4  12.2  0.12  0.885
Error   22  2179.0  99.0
Total   24  2203.4
S = 9.952   R-Sq = 1.11%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  ---------+---------+---------+---------+
1      7  58.286   7.631  (---------------*--------------)
2      9  60.667  11.779         (------------*-------------)
3      9  60.222   9.484        (------------*-------------)
                          ---------+---------+---------+---------+
                                55.0      60.0      65.0      70.0
Pooled StDev = 9.952
```

Pass 2, Big Shoe, Load Cells 1-4

```
Source  DF     SS    MS     F      P
C18      2   13.9   7.0  0.35  0.712
Error   13  260.0  20.0
Total   15  273.9
S = 4.472   R-Sq = 5.09%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on pooled StDev
Level  N    Mean  StDev    +---------+---------+---------+---------
1      6  57.000  6.197           (------------*------------)
2      5  55.200  3.114    (-------------*-------------)
3      5  57.400  2.702           (-------------*--------------)
                           +---------+---------+---------+---------
                         51.0      54.0      57.0      60.0
Pooled StDev = 4.472
```

Pass 2, Big and Small Shoe, Load Cells 1-4

```
Source  DF      SS     MS     F      P
C56      1   104.8  104.8  1.65  0.207
Error   39  2477.3   63.5
Total   40  2582.1
S = 7.970   R-Sq = 4.06%   R-Sq(adj) = 1.60%

                          Individual 90% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  -------+---------+---------+---------+--
B      16  56.563  4.273  (------------*-------------)
S      25  59.840  9.582                 (---------*----------)
                          -------+---------+---------+---------+--
                              55.0      57.5      60.0      62.5
Pooled StDev = 7.970
```

Pass 3, Small Shoe, Load Cells 1-4

```
Source   DF     SS    MS     F      P
C22       2   30.6  15.3  0.65  0.531
Error    21  492.8  23.5
Total    23  523.3
S = 4.844   R-Sq = 5.84%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -----+---------+---------+---------+----
1      8  56.500  5.237         (-------------*-------------)
2      8  57.625  5.041             (--------------*-------------)
3      8  54.875  4.190  (--------------*-------------)
                         -----+---------+---------+---------+----
                           52.5      55.0      57.5      60.0
```

Pass 3, Big Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
C26       2    60.1  30.1  0.44  0.649
Error    15  1013.5  67.6
Total    17  1073.6
S = 8.220   R-Sq = 5.60%   R-Sq(adj) = 0.00%

                          Individual 95% CIs For Mean Based on
                          Pooled StDev
Level  N    Mean   StDev  -------+---------+---------+---------+--
1      6  53.667   6.377  (-------------*--------------)
2      6  57.833  10.998          (--------------*-------------)
3      6  54.333   6.408   (--------------*-------------)
                          -------+---------+---------+---------+--
                              50.0      55.0      60.0      65.0
Pooled StDev = 8.220
```

Pass 3, Big and Small Shoe, Load Cells 1-4

```
Source   DF      SS    MS     F      P
C62       1    11.5  11.5  0.29  0.595
Error    40  1596.9  39.9
Total    41  1608.4
S = 6.319   R-Sq = 0.71%   R-Sq(adj) = 0.00%

                          Individual 90% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --------+---------+---------+---------+-
B      18  55.278  7.947  (----------------*---------------)
S      24  56.333  4.770           (--------------*-------------)
                          --------+---------+---------+---------+-
                               54.0      55.5      57.0      58.5
Pooled StDev = 6.319
```

Pass 1 to 3, Small Shoe, Load Cells 1-4

```
Source  DF      SS     MS      F      P
C31      2  1687.0  843.5  10.30  0.000
Error   68  5566.0   81.9
Total   70  7252.9
S = 9.047   R-Sq = 23.26%   R-Sq(adj) = 21.00%

                           Individual 95% CIs For Mean Based on
                           Pooled StDev
Level   N    Mean   StDev  -----+---------+---------+---------+----
a      22  68.182  11.628                          (------*-------)
b      25  59.840   9.582         (-------*------)
c      24  56.333   4.770  (-------*------)
                           -----+---------+---------+---------+----
                              55.0      60.0      65.0      70.0
Pooled StDev = 9.047
```

Pass 1 to 3, Big Shoe, Load Cells 1-4

```
Source  DF    SS   MS     F      P
C37      2   129   64  0.59  0.556
Error   45  4876  108
Total   47  5005
S = 10.41   R-Sq = 2.57%   R-Sq(adj) = 0.00%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N   Mean  StDev  ----+---------+---------+---------+-----
a      14  59.29  16.48          (-------------*-------------)
b      16  56.56   4.27    (------------*------------)
c      18  55.28   7.95  (-----------*-----------)
                         ----+---------+---------+---------+-----
                           52.0      56.0      60.0      64.0
Pooled StDev = 10.41
```